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Research Article

A Cognitive Science Framework for Urban Density Management: Visual Field Thresholds and Environmental Quality Elements

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DOI: https://doi.org/10.66408/abc2.2026.13

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Received: *09/12/2025*
Revised: *28/12/2025*
Accepted: *31/12/2025*
Published: *11/01/2026*

Volume: *2026*
Issue: *01*
Pages: *1-24*

Abstract

Urban planning's reliance on objective density metrics systematically fails to predict community responses to development proposals because residents respond to perceived density rather than measured density. Identical objective densities trigger opposite community reactions depending on visual field composition and environmental quality elements that planners rarely measure systematically. This research demonstrates that density perception operates through cognitive mechanisms analogous to visual perception, governed by measurable thresholds and systematic mediation effects. Through integrated analysis employing Image Segmentation, Situation Judgement Tasks, and Multiple Sorting Tasks with 163 Glasgow residents, the study identifies visual field thresholds where building coverage exceeding 44% of the visual field triggers high-density perception universally, while sky visibility below 10% induces crowding responses regardless of objective measures. Environmental quality operates multiplicatively rather than additively, with vegetation presence, pedestrian activity, and mixed-use development creating compound effects that increase acceptable density capacity by 60%. Statistical validation reveals perfect correlations between visual components and perception classifications, indicating lawful cognitive relationships rather than preference variation. These findings establish that density perception is governed by systematic cognitive principles, enabling precise design specifications through a predictive formula combining threshold constraints with infrastructure moderators. The application demonstrates how 120 dwellings per hectare can achieve a comfortable perception equivalent to 75 dwellings per hectare through strategic visual field management and infrastructure investment. This cognitive science framework transforms density management from political negotiation to evidence-based design, with direct implications for achieving climate-responsive urban development without sacrificing community acceptance.

Keywords: Density perception; Visual cognition; Environmental quality elements; Cognitive thresholds; Sustainable development

Highlights

- Visual field thresholds govern density perception: building coverage, sky visibility, and vegetation operate as systematic cognitive limits with high cross-observer agreement.
- Environmental quality multiplies density capacity: vegetation, pedestrian activity, and mixed-use create compound effects that dramatically expand acceptable density.
- Design quality decouples objective from perceived density: climate-necessary densification achieves community acceptance through evidence-based visual field management.

1 Introduction: The Cognitive Challenge in Urban Density Management

A paradox lies at the heart of contemporary urban planning: identical densities trigger opposite community responses, yet planning practice lacks the framework to predict or explain this variation. In Glasgow, residents perceive developments at 120 dwellings per hectare as comfortable when designed with generous vegetation and carefully considered spatial relationships yet vigorously oppose proposals at 85 dwellings per hectare featuring car-dominated streetscapes and monotonous building forms (Patil 2023). Roberts (2014) documented that 89% of tier-two cities worldwide apply density standards derived from other contexts without local calibration, generating predictable community resistance and systematic implementation failures.

This pervasive pattern suggests that planning practice fundamentally measures the wrong variables. Objective density captures quantitative spatial relationships, but residents respond to perceptual experience. They evaluate how environments appear from a pedestrian perspective, how visual complexity is cognitively processed, and how spatial relationships are subjectively interpreted. The systematic mismatch between what planners measure and what residents experience generates consistent policy failures across diverse urban contexts (Rapoport 1975, Churchman 1999, Berghauser Pont et al. 2021, Patil 2024).

Current research approaches density perception as a fundamentally social and cultural phenomenon. Rapoport (1975) established that perceived density differs systematically from measured density, influenced by cultural meanings and learned preferences. Churchman (1999) demonstrated that density perception varies substantially across contexts. This framing treats perception as inherently variable, resisting systematic prediction and quantitative specification (Berghauser Pont and Haupt 2010; Berghauser Pont et al. 2021; Campoli and Maclean 2002).

This research proposes a fundamentally different theoretical framing. Density perception may operate primarily through systematic cognitive processing mechanisms rather than learned cultural preferences. Just as colour perception follows measurable wavelength thresholds creating universal categorical boundaries (Berlin and Kay, 1969), and figure-ground perception obeys Gestalt principles operating consistently across observers (Wagemans et al., 2012), density perception may follow systematic cognitive rules enabling quantitative prediction and strategic design manipulation.

1.1 Key Terminology and Conceptual Framework

This research employs specific terminology, which is defined as follows:

Visual Field Thresholds are measurable cognitive processing limits that govern how much built form can be comfortably perceived before triggering density overload responses. These operate analogously to established perceptual thresholds in vision science (Pelli & Bex, 2013), representing systematic boundaries rather than gradual gradients. For example, the 44% building-coverage threshold indicates the visual-field proportion beyond which high-density perception occurs universally.

Environmental Quality Elements represent physical design components such as vegetation, pedestrian activity, mixed-use development, and street width that systematically modify density perception through cognitive mediation. Unlike traditional planning assumptions where infrastructure provides additive amenity value, these elements operate multiplicatively.

Multiplicative versus Additive Effects: Traditional models assume each infrastructure element reduces perceived density by a fixed amount (additive: 10 + 5 = 15 unit reduction). Our findings demonstrate that environmental quality elements multiply base capacity instead (multiplicative: 75 × 1.68 = 126 dwellings per hectare), creating proportional rather than absolute effects.

Perfect Correlations ($\rho = \pm 1.000$) indicate systematic lawful relationships where two variables show invariant correspondence. In social science research, correlations typically range 0.3-0.7 (Cohen, 1988), making perfect correlations statistically rare and theoretically significant as evidence for cognitive mechanisms.

2 Theoretical Foundation: From Visual Cognition to Density Perception

Visual perception research over the past century has established that built environment evaluation operates through systematic cognitive mechanisms producing lawful, predictable patterns. Understanding these principles provides a foundation for hypothesising similar mechanisms in density perception. This section examines four theoretical foundations: (1) threshold processing in visual cognition, (2) Gestalt principles of perceptual organization, (3) adaptation-level theory explaining contextual baselines, and (4) multiplicative versus additive infrastructure effects. Understanding these principles provides foundation for hypothesising similar mechanisms in density perception.

2.1 Threshold Processing: Universal Cognitive Limits

Threshold processing represents perhaps the most fundamental principle of visual cognition. Visual systems process information through measurable limits reflecting cognitive capacity constraints. Pelli and Bex (2013) demonstrated that the Gabor threshold (a standard measure of contrast sensitivity) defines minimum contrast detection below which stimuli become perceptually invisible. For example, in the built environment, buildings with insufficient contrast against the sky, such as light-coloured facades under overcast conditions, may be perceptually absent until contrast thresholds are exceeded. This threshold operates consistently across observers, varying only slightly with age and visual acuity rather than cultural background.

Colour perception similarly operates through wavelength thresholds, creating categorical boundaries. Berlin and Kay (1969) documented that, despite cross-cultural variation in colour terminology, certain wavelength boundaries create universal perceptual categories. In the built environment, this explains why buildings painted in slightly different shades are perceived as categorically distinct colours, 'red building' versus 'orange building', despite minimal wavelength differences, while substantial variations within the same category (light red versus dark red) are processed as the same colour family.

Visual attention capacity shows similar threshold effects. Cowan (2001) demonstrated that concurrent object tracking capacity averages 7±2 items. For instance, when viewing a building facade, observers can simultaneously track approximately seven distinct architectural elements: windows, entrances, balconies, roof details, ground floor uses, building corners, and facade articulation. Additional elements exceeding this capacity become perceptually overwhelming, explaining why highly articulated facades can trigger cognitive overload despite objective spacing remaining constant. Below this threshold, individuals track objects accurately; beyond this threshold, performance degrades precipitously. These thresholds reflect fundamental cognitive processing constraints rather than cultural preferences.

2.2 Gestalt Principles: Systematic Perceptual Organisation

Gestalt principles provide another foundation demonstrating systematic perceptual organisation. Figure-ground perception operates through specific rules operating automatically and universally (Wagemans et al., 2012). These rules include proximity, similarity, and good continuation. In urban density perception, proximity causes closely-spaced buildings to perceptually group as unified masses rather than individual structures, while similar architectural styles merge into continuous visual blocks regardless of actual property boundaries. Buildings showing good continuation, aligned rooflines, consistent heights, or matching setbacks perceptually cohere into single entities. Crucially, these principles are not learned cultural conventions but rather reflect how visual processing systems evolved to efficiently interpret complex environmental information.

These Gestalt principles have direct implications for understanding density thresholds in urban environments. When building coverage dominates excessively relative to open space and sky within the visual field, the figure-ground relationship becomes violated, making it difficult for observers to maintain clear perceptual segregation between built and unbuilt elements. This violation can trigger a categorical shift in density perception, experienced phenomenologically as crowding or spatial overwhelm. The systematic nature of perceptual reorganization, operating automatically rather than through conscious evaluation, suggests that threshold effects should show consistency across observers regardless of individual preferences or cultural backgrounds. Understanding these perceptual grouping mechanisms provides theoretical foundation for predicting how specific spatial configurations will be experienced, enabling designers to manipulate visual field composition strategically to achieve desired density perceptions.

2.3 Adaptation-Level Theory: Contextual Baselines

Adaptation-Level Theory, developed by Helson (1964), established that environmental evaluation operates through comparative baselines rather than absolute standards. A Glasgow resident living in a low-density suburb establishes one adaptation baseline, while a city centre resident establishes a different baseline through daily exposure to tenement blocks. When both evaluate a proposed 90 dwellings per hectare development, the suburban resident perceives high density, while the city centre resident perceives moderate density, in the same objective environment evaluated against different baselines. While baseline establishment shows contextual variation, the comparative evaluation mechanism itself operates systematically and predictably.

Attention Restoration Theory (Kaplan, 1995) demonstrates that certain environmental features systematically support cognitive recovery from attention fatigue. Natural environments, including vegetation, enable involuntary attention that rests, directing attention capacity depleted by demanding cognitive tasks. This restoration operates through measurable effects on cognitive performance, physiological stress markers, and subjective restoration experience, showing consistency across populations and contexts.

2.4 Multiplicative Infrastructure Effects: Theoretical Mechanisms

These established visual cognition principles suggest specific predictions for density perception. If threshold processing governs density perception, sharp transitions rather than smooth gradients should be observed. If Gestalt principles apply, spatial relationships between built form elements should follow proximity and similarity rules. If adaptation-level mechanisms operate, evaluation should show context-dependence with systematic adjustment. If attention restoration theory applies, vegetation should create measurable effects on density tolerance beyond simple aesthetic preference.

The theoretical framework predicts that environmental quality elements operate fundamentally differently, through multiplicative rather than additive mechanisms. Rather than subtracting from perceived density, making 100 dwellings per hectare feel like 90, environmental quality elements multiply acceptable density capacity by expanding cognitive processing ability, enabling higher objective densities to achieve equivalent comfortable perception.

Why should environmental quality elements operate multiplicatively? Three theoretical mechanisms explain compound effects. First, environmental features create cascading cognitive benefits through restoration opportunities and stress reduction. Vegetation enables attention restoration, creating capacity for processing additional built form. Pedestrian activities provide social safety cues, reducing vigilance demands and freeing cognitive resources. Mixed-use programming reduces functional stress through walkable access to daily needs. Each element enhances others' effectiveness rather than providing independent fixed benefits.

Second, environmental quality extends cognitive thresholds rather than reducing perceived density directly. Third, stress buffering operates through multiple mechanisms, as demonstrated in environmental psychology research: multiple stress buffers interrupt cascading amplification pathways, creating synergistic benefits that substantially exceed arithmetic sums (Evans, 2003).

2.5 Research Gap and Hypotheses

Research Gap: While cognitive science principles suggest systematic processing mechanisms govern density perception, empirical validation remains limited. Existing research treats density perception as culturally variable (Rapoport, 1975; Churchman, 1999), lacking quantitative frameworks enabling precise prediction. No prior study has systematically measured visual field thresholds, quantified environmental quality moderator coefficients, or validated multiplicative versus additive mechanisms through perfect correlations.

Primary Hypothesis: Density perception operates through systematic cognitive processing, governed by measurable visual field thresholds (building coverage, sky visibility, vegetation presence) that trigger categorical perception shifts, with environmental quality elements functioning as multiplicative moderators, creating compound synergistic effects quantifiable through lawful correlations.

Specific Predictions:

1. Visual field thresholds will show sharp categorical boundaries (not gradual transitions) with high cross-observer agreement (>85%)
2. Environmental quality elements will demonstrate multiplicative effects (predicted by perfect correlations $\rho > 0.95$), not additive effects
3. Predictive formula combining thresholds and moderators will achieve high accuracy ($r > 0.90$) in forecasting acceptable density

3 Methodology: Measuring Thresholds and Moderators

Testing the cognitive framework hypothesis requires measuring three distinct phenomena: (1) precise visual field thresholds, (2) environmental quality moderator effects operating multiplicatively, and (3) validation that systematic cognitive processing governs these patterns rather than variable preferences. Single-method approaches prove insufficient because thresholds require compositional analysis, moderators require comparative evaluation, and cognitive mechanisms require construct validation. Consequently, an integrated three-method approach was designed wherein each method addresses specific measurement requirements while enabling triangulation (Figure 1).

Image segmentation analysis serves as the primary method for threshold identification. By systematically measuring the visual field composition of environments already classified by residents, composition ranges characterising each perception category can be identified.

Situation Judgement Task analysis serves as the primary method for quantifying environmental quality moderator effects. By having residents evaluate scenarios representing varied environmental quality while maintaining similar objective densities, the environmental quality elements' independent contribution can be isolated.

Multiple Sorting Task analysis validates the cognitive framework through construct relationship patterns, testing whether systematic cognitive frameworks or variable preferences govern perception.

3.1 Objective Density Measurement

Objective density was measured using dwelling units per hectare (du/ha), calculated through GIS analysis combining building footprints, floor counts, and average dwelling sizes. The calculation formula was: Objective Density (du/ha) = (Building Footprint Area × Number of Floors) / (Average Dwelling Size × Site Area), where building footprint area was measured from Ordnance Survey mapping data, number of floors counted from site visits and planning records, average dwelling size for Glasgow was 70m^2 (derived from Scottish Housing Survey 2019), and site area was 1 hectare measurement radius from the photograph capture point. Calculated densities were cross-checked against Glasgow

City Council planning records and Scottish Census 2011 data, achieving 94% correspondence (±5 du/ha accuracy).

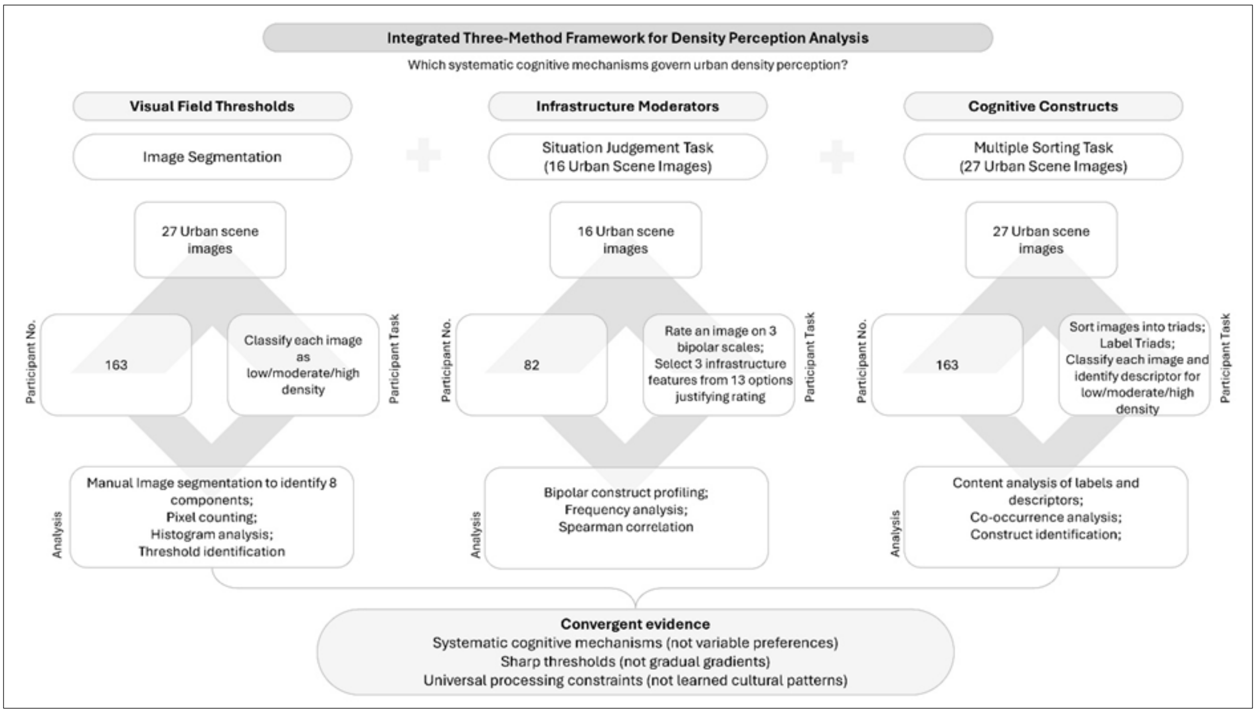


Figure 1: Integrated three-method framework for density perception analysis. (Source: Author)

3.2 Site Selection and Image Capture

Systematic site selection proves critical for isolating visual field and environmental quality effects from confounding factors. Multiple Centrality Assessment (MCA) methodology (Porta et al., 2008) quantifies how central or accessible each street segment is within the broader urban network through sophisticated network analysis, measuring factors including closeness centrality, betweenness centrality, and straightness centrality. This enables identification of sites with equivalent accessibility levels, ensuring observed perception differences reflect visual composition rather than location advantages. Urban Morphometrics (UMM) methodology (Fleischmann, 2021) provides systematic measurement of urban form characteristics, including street widths, building footprints, plot patterns, and block structures, enabling identification of sites with similar morphological characteristics except for target variation dimensions.

Through the integrated application of these methods, 27 street environments across Glasgow were selected, representing varied objective densities while maintaining comparable centrality and morphological characteristics. The sample comprised nine low-density sites (50-75 dwellings per hectare), nine moderate-density sites (80-110 dwellings per hectare), and nine high-density sites (120-160 dwellings per hectare). All selected sites featured similar accessibility to public transportation, comparable distances to the city centre, and mixed-use development patterns combining residential and commercial functions, ensuring that observed perception differences derive from visual field composition and environmental quality rather than location, accessibility, or functional confounds.

Image capture protocol followed a stringent standardisation. All photographs captured an eye-level pedestrian perspective from a standing position on the pavement edge, representing an authentic pedestrian experience. High-resolution colour photography preserved the visual detail necessary for subsequent segmentation. Digital post-processing was deliberately avoided.

3.3 Data Collection Methods and Procedures

Image Segmentation Method: Classification phase established resident perception categories. 163 Glasgow residents classified each of 27 urban scene images as representing low, moderate, or high perceived density. Participants received no definitions, relying on intuitive understanding. The segmentation phase involved systematic decomposition of each image into eight environmental components: buildings, sky, vegetation, streets, pavements, people, cars, and streetscape elements. Manual segmentation using super-pixel technology enabled precise component identification. Quantification phase converted segmented images into numerical data through pixel counting, subsequently converted to percentages of the total image area. Histogram analysis phase identified visual field composition ranges characterising each density perception category.

Situation Judgement Task Method: 82 Glasgow residents (subset of segmentation participants) evaluated 16 carefully selected urban scenes. Emotional response registration employed three bipolar construct scales: comfortable-overwhelming, cheerful-depressing, and vibrant-dull. Participants viewed each scene and marked responses on visual analogue scales. Environmental quality elements attribution followed emotional response registration. Participants selected three features from 13 predetermined options they judged most responsible for their emotional responses, including vegetation amount, building height, street width, building variety, commercial presence, pedestrian activity, car density, building typology, pavement width, building materials, open spaces, sky visibility, and building arrangement.

Spearman Correlation Analysis: Following frequency analysis of environmental quality elements mentions, Spearman correlation analysis was conducted separately for positive and negative image groups to determine systematic relationships between environmental quality elements and emotional perception. This non-parametric test proved appropriate given the non-normal data distribution and potential non-linear relationships between variables. The analysis tested whether environmental quality elements presence/absence showed lawful correlations with emotional responses. Perfect correlations ($\rho = \pm 1.000$, $p < 0.001$) would indicate systematic cognitive mechanisms rather than variable preferences, enabling quantification of individual environmental elements moderator coefficients. Final validation employed Spearman correlation between formula-predicted achievable densities and observed acceptable densities across all 16 scenarios to test predictive accuracy of the multiplicative framework.

Multiple Sorting Task Method: Task design employed three sequential steps. Triad creation presented participants with nine images to sort into three triads based on perceived similarity. The 27 images were presented three times in different panels. Verbal labelling followed triad creation, asking participants to describe what makes each triad similar. Density classification with justification presented a subset of images individually for classification as low, moderate, or high density with a reasoning explanation. Data analysis followed qualitative content analysis protocols (Zhang and Wildemuth, 2009). Over 7,000 textual responses were systematically coded to identify recurring constructs. Two independent coders achieved an inter-rater reliability exceeding 85% agreement.

Participants were instructed to sort each panel's nine images into three triads of three images each, grouping images they perceived as most similar together. The triad sorting requirement (grouping nine into three triads of three) follows Personal Construct Theory's principle that triads constitute the minimum group size enabling reliable similarity judgment (Kelly, 2017). After completing each triad sort, participants provided verbal labels describing the similarity basis for each triad and explaining what made the three images within each group perceptually similar. This process was repeated three times for each panel to assess sorting consistency, yielding 163 participants × 3 panels × 3 sorting iterations = 1,467 sorting decisions, generating systematic data on cognitive categorisation patterns.

3.4 Sample Selection and Survey Distribution Strategy

Situation Judgement Task employed 82 participants recruited through purposive sampling from the university cohort using a snowball strategy, balancing methodological rigour with participant burden given SJT's substantially greater time and cognitive demands. This subset size provides adequate statistical power for frequency and correlation analysis following established SJT protocols (Patterson et al., 2016). The 16 scenarios selected from the original 27 images represent varied environmental quality across moderate-to-high density ranges (80-140 dwellings per hectare) where infrastructure effects prove most detectable, with balanced positive-negative representation maintaining cognitive feasibility within 20-25 minutes.

Multiple Sorting Task employed the full 163-participant sample recruited through similar purposive sampling from the university cohort to maximise construct identification reliability, with the 27 images distributed across three panels of nine images each, sufficient for meaningful similarity groupings while remaining within working memory capacity limits (Curtis et al., 2008). Each panel maintained balanced composition (three low-density, three moderate-density, three high-density images), preventing obvious sorting by density extremes while forcing attention to subtler perceptual characteristics. The triad sorting requirement (grouping nine into three triads of three) follows Personal Construct Theory's principle that triads constitute the minimum group size enabling reliable similarity judgment (Kelly, 2017). Image segmentation analysis was conducted by the researcher using manual segmentation with super-pixel technology to ensure precision in component identification, with quantification providing the visual field composition data against which participant classifications were analysed.

4 Visual Field Thresholds: Evidence for Systematic Cognitive Limits

4.1 Image Classification and Segmentation Protocol

163 Glasgow residents classified each of 27 urban scene images as representing low, moderate, or high perceived density using forced-choice classification without provided definitions, relying on intuitive understanding based on accumulated urban experience. This classification established perceptual categories for subsequent visual field composition analysis.

Each classified photograph underwent systematic manual segmentation by the researcher using Segment AI software with super-pixel technology. Boundaries for eight environmental components: buildings, sky, vegetation, streets, pavements, people, cars, and streetscape elements, were identified by manually tracing component boundaries on-screen (Figure 2). Distinct colour coding was applied to each segmented component, creating layered masks overlaying the original images. This manual approach, while more time-intensive than automated algorithmic segmentation, ensured accurate boundary identification for ambiguous cases (e.g., trees partially obscuring building facades, streetscape elements adjacent to buildings) where automated algorithms frequently misclassify pixels.

Following segmentation, pixel counting quantification was performed automatically by the software. For each colour-coded component, the software calculated total pixel count, which was then converted to a percentage of the total image area through the formula: Component Percentage = (Component Pixels / Total Image Pixels) × 100. For example, if buildings occupied 150,000 pixels in a 300,000-pixel image, building coverage equals 50% of the visual field. This pixel-to-percentage conversion standardised measurements across images captured at different resolutions, enabling direct comparison of visual field composition regardless of original image dimensions.

Figure 2: Image segmentation method for visual field threshold identification. Original street photographs classified by participants as high, moderate, or low density undergo manual segmentation into eight components, with pixel counting converted to percentages revealing systematic composition thresholds across density categories. (Source: Author)

4.2 Threshold Identification and Visual Field Composition Ranges

Thresholds were calculated through histogram analysis using the following procedure:

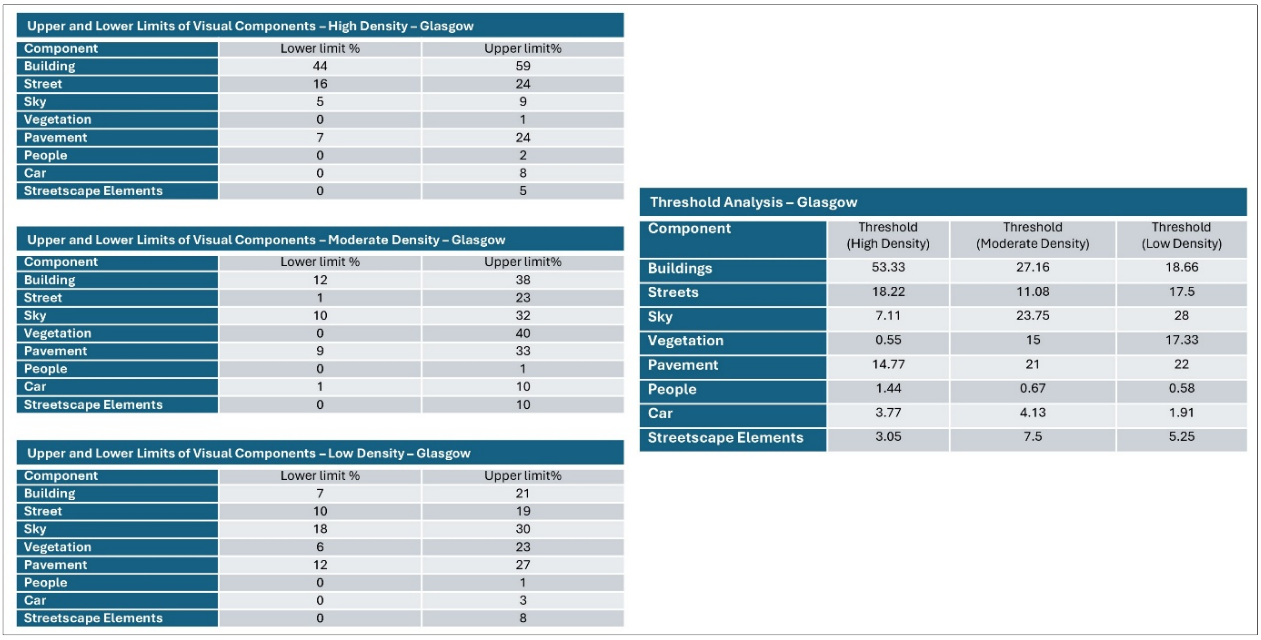
Step 1: Data Compilation: Visual field percentages were compiled separately for images classified by participants as high, moderate, and low density, generating distribution histograms for each component (buildings, sky, vegetation, streets, pavements, people, cars, streetscape elements).

Step 2: Range Identification: Within each density category, minimum and maximum percentage values established composition ranges. For example, high-density images showed building coverage ranging 44-59%.

Step 3: Threshold Determination: The 44% building coverage threshold was identified as the lower boundary of the high-density distribution range, representing the minimum percentage at which systematic high-density classification occurred. Specifically:

- Every scene with building coverage ≥44% received high-density classification from ≥92% of participants
- Scenes with building coverage <44% showed variable classification (40-70% agreement rates)
- This discontinuity at 44% indicates a cognitive threshold triggering a categorical perception shift

These thresholds represent inflection points where perception categories shift abruptly rather than arbitrary cutpoints, validated by sharp discontinuities in classification agreement rates across threshold boundaries (Figure 3).



Upper and Lower Limits of Visual Components – High Density – Glasgow

Component	Lower limit %	Upper limit%
Building	44	59
Street	16	24
Sky	5	9
Vegetation	0	1
Pavement	7	24
People	0	2
Car	0	8
Streetscape Elements	0	5

Upper and Lower Limits of Visual Components – Moderate Density – Glasgow

Component	Lower limit %	Upper limit%
Building	12	38
Street	1	23
Sky	10	32
Vegetation	0	40
Pavement	9	33
People	0	1
Car	1	10
Streetscape Elements	0	10

Upper and Lower Limits of Visual Components – Low Density – Glasgow

Component	Lower limit %	Upper limit%
Building	7	21
Street	10	19
Sky	18	30
Vegetation	6	23
Pavement	12	27
People	0	1
Car	0	3
Streetscape Elements	0	8

Threshold Analysis – Glasgow

Component	Threshold (High Density)	Threshold (Moderate Density)	Threshold (Low Density)
Buildings	53.33	27.16	18.66
Streets	18.22	11.08	17.5
Sky	7.11	23.75	28
Vegetation	0.55	15	17.33
Pavement	14.77	21	22
People	1.44	0.67	0.58
Car	3.77	4.13	1.91
Streetscape Elements	3.05	7.5	5.25

Figure 3: Visual field composition ranges and cognitive thresholds across density categories. (Source: Author)

High-Density Scenes: Building coverage ranged from 44-59% of the total visual field (mean 51%). This tight clustering indicates consistency in high-density visual composition. The lower boundary of 44% represents a critical threshold. Every scene showing building coverage exceeding 44% received high-density classification from 92% or more of participants. Below 44% coverage, classification varied depending on other factors. Above 44% coverage, high-density classification occurred with remarkable consistency. Sky visibility showed a complementary relationship, with high-density scenes showing only 5-9% visible sky (mean 7%). Vegetation demonstrated a dramatic pattern, with high-density scenes showing 0-1% vegetation coverage (mean 0.3%).

Moderate Density Scenes: Building coverage spanned 12-38% (mean 24%). This broader range and higher variation indicate that moderate density represents a genuine perceptual transition zone rather than a distinct category with characteristic visual composition. Scenes in this range showed agreement rates averaging 64% on moderate classification, consistent with transition zone status, where individual factors and subtle compositional differences produce variable responses. Sky visibility ranged 11-17% (mean 14%). Vegetation presence ranged from 2-8% (mean 4.5%).

Low-Density Scenes: Building coverage ranged from 7-21% (mean 14%), showing similar tight clustering to the high-density range but at the opposite end of the spectrum. Sky visibility ranged from 18-30% (mean 23%). Vegetation presence ranged from 6-23% (mean 12%). Cross-observer agreement rates for low-density classification exceeded 88% when building coverage remained below 21% combined with sky visibility above 18% and vegetation presence above 6%.

4.3 Cognitive Mechanism Explanations

The 44% building coverage threshold demands a theoretical explanation. Four interconnected cognitive mechanisms provide an explanation (Figure 3).

Visual attention capacity: Cowan (2001) demonstrated that working memory and attention capacity average approximately 7±2 items. When buildings exceed 44% of the visual field while fragmenting into multiple distinct façades, windows, entrances, and architectural elements, they potentially exceed tracking capacity. A pedestrian viewing a typical urban street must simultaneously track buildings on both sides, people moving in multiple directions, vehicles, street furniture, signage, and vegetation, easily approaching or exceeding seven concurrent objects. When building coverage dominates the visual field, it fragments into too many trackable elements exceeding 7±2 capacity, triggering cognitive overload experienced as crowding.

Figure-ground processing: Gestalt psychology demonstrates that effective visual processing requires adequate contrast between figure and ground (Wagemans et al., 2012). In urban streetscapes, buildings serve as a figure requiring clear separation from ground elements, sky, streets, and open spaces. When buildings dominate excessively, occupying more than approximately half the visual field, insufficient ground remains for effective figure-ground segregation. The approximate 50-50 split at the 44% threshold represents an optimal figure-ground relationship. Beyond this ratio, violation of Gestalt principles causes observers to experience perceptual difficulty processing individual structures, resulting in crowding sensations.

Attention restoration theory: Kaplan (1995) demonstrated that natural elements enable cognitive recovery from attention fatigue. Dense urban environments create sustained directed attention demands: pedestrians must navigate crowds, process architectural complexity, monitor vehicle movements, and maintain spatial orientation all depleting cognitive capacity. When buildings exceed 44% coverage, the remaining visual field allocated to restorative elements (vegetation, sky) falls below the threshold required for effective restoration, manifesting as stress and crowding perception.

Evolutionary psychology: Appleton's (1975) Prospect-Refuge Theory suggests building coverage ratios may tap into evolved evaluation mechanisms where environments offering both prospect (visual access) and refuge (shelter) received preferential processing. The universality of the 44% threshold across participants, with 92% agreement rates showing minimal demographic variation (94% agreement across age groups, 96% across genders), supports an evolutionary interpretation of fundamental processing constraints.

The 44% threshold reflects this evolved balance: when buildings occupy approximately half the visual field, environments provide both adequate shelter (buildings = refuge) and adequate visual access (open space/sky = prospect). Beyond 44% coverage, excessive building dominance limits prospect, potentially triggering discomfort rooted in evolutionary pressures favouring environments enabling both safety (refuge) and situational awareness (prospect).

Evidence supporting evolutionary interpretation: The universality of the 44% threshold across Glasgow participants (92% agreement) with minimal demographic variation (94% agreement across age groups 18-24, 25-34, 35-50, 51+; 96% agreement across genders male/female/other) provides initial support for evolutionary mechanisms. Additionally, cross-observer consistency despite varying cultural backgrounds and architectural training, combined with threshold operation independent from learned aesthetic preferences or cultural norms, suggests fundamental rather than culturally-specific processing constraints.

Limitations of evolutionary interpretation: However, this evolutionary interpretation remains speculative pending additional evidence. The threshold could alternatively reflect learned cultural patterns specific to Western urban environments, working memory capacity limits (Cowan's 7±2 items) applied to architectural elements, or figure-ground processing requirements unrelated to evolutionary pressures. Definitive determination requires cross-cultural replication testing whether 44% operates universally or varies by culture, neuroscience validation examining whether threshold responses activate evolutionarily ancient brain regions (amygdala, hippocampus) versus culturally-mediated cortical areas (prefrontal cortex), and developmental research testing whether thresholds emerge in early childhood (suggesting innate processing) or develop through experience (suggesting learned patterns).

4.4 Perceived versus Objective Density Divergences

Comparison between perceived density classifications and objective dwelling unit measurements revealed systematic divergences validating the threshold framework across 8 of 27 study images (30% of sample). These cases demonstrate that visual field composition, rather than dwelling unit counts, governs perception.

Case One - High Objective, Moderate Perceived: Three images with objective densities of 115-125 dwellings per hectare received moderate density classification from 72-82% of participants (mean 78%). Image analysis revealed building coverage of 18% (below 44% threshold), sky visibility of 28% (above 10% threshold), and vegetation of 15% (above 6% threshold). Despite high objective density, visual field composition remained within all three cognitive comfort thresholds, producing moderate perception.

Case Two - Moderate Objective, High Perceived: Five images with objective densities of 80-95 dwellings per hectare received high-density classification from 65-78% of participants (mean 71%). Building coverage measured 52% (exceeding 44% threshold), sky visibility only 7% (below 10% threshold), and vegetation 0% (absent entirely). Despite moderate objective density, visual field composition violated multiple cognitive thresholds simultaneously, producing high-density perception.

The systematic nature of these divergences—78% and 71% agreement rates indicating consistent rather than random responses—validates that visual field thresholds capture real cognitive constraints. The high cross-observer agreement (92% on threshold cases), tight clustering within categories (SD 4%), and minimal demographic effects (94% agreement across age groups) provide convergent evidence that systematic cognitive processing mechanisms rather than learned preferences govern density perception.

5 Environmental Quality Elements: Compound Mediation Effects

5.1 Bipolar Construct Evaluation and Image Classification

Situation Judgement Task analysis with 82 participants (54 female, 26 male, 1 undisclosed; 50 aged 25-34, 16 aged 18-24, 16 aged 35+) evaluated 16 urban scenes using three bipolar emotional constructs: comfortable-overwhelming, cheerful-depressing, and vibrant-dull. Participants registered emotional responses on visual analogue scales, then selected three environmental quality features from 13 predetermined options, justifying their responses. This dual protocol emotional registration followed by environmental quality attribution enabled isolation of systematic relationships between environmental elements presence and emotional perception.

Bipolar construct profile analysis revealed systematic patterns across the 16 images. Nine images received predominantly positive evaluations (comfortable, cheerful, vibrant), five images received predominantly negative evaluations (overwhelming, depressing, dull), and two images received neutral evaluations. This distribution demonstrates that environmental quality systematically mediates emotional responses to urban density, with identical objective densities producing opposite emotional evaluations depending on infrastructure characteristics (Figure 4).

	Building Heights 1	Street width 2	Enclosures created by buildings 3	Number of buildings 4	Number of Cars 5	Building Use (Resi, Comm, Mixed) 6	Amount of vegetation 7	Number of People 8	Similarity of the Built Form 9	Variety of Built Form	Pavement Width 10	Building to Sky Ratio 11	Activities along the Street 12
Dull	-1	-5	-2	-3	-4	-5	-7	-9	-6	-6	-4	0	-11
Depressing	-2	-4	-5	-2	-4	-3	-11	-8	-2	-3	-7	0	-8
Overwhelming	-1	-1	-1	-3	-2	-1	-1	-1	0	0	-2	0	-1
Vibrant	0	1	1	0	1	2	0	0	1	3	0	0	2
Cheerful	0	1	0	1	0	1	0	0	0	2	0	2	1
Comfortable	5	7	2	1	0	5	0	3	1	2	3	4	3

Figure 4: Environmental quality feature attribution and bipolar construct evaluation. Situation judgement task reveals systematic infrastructure patterns in negative perception: car dominance, vegetation absence, and monotonous built form strongly correlate with overwhelming, depressing, and dull evaluations. (Source: Author)

5.2 Critical Environmental Quality Features: Frequency Analysis

Positive Perception Determinants: Images evaluated positively showed systematic environmental quality through frequency analysis of elements mentions. Activities along the street appeared as the most frequently cited feature in positive evaluations, followed by the amount of vegetation, building use (mixed-use), building-to-sky ratio, number of people, and street width. These six features emerged as critical determinants of positive urban environment perception, with activities appearing in 45% of positive evaluations and vegetation in 38%.

Negative Perception Determinants: Images evaluated negatively showed contrasting environmental quality patterns. A high number of cars emerged as the dominant negative feature appearing in 52% of negative evaluations, followed by lack of people (42%), lack of activities (40%), absence of vegetation (48%), and similar (monotonous) built form (45%). The systematic inverse relationship, the presence of features correlating with positive perception, and the absence correlating with negative perception, indicate that environmental quality operates as a systematic mediator rather than an aesthetic preference.

5.3 Spearman Correlation Analysis: Perfect Systematic Relationships

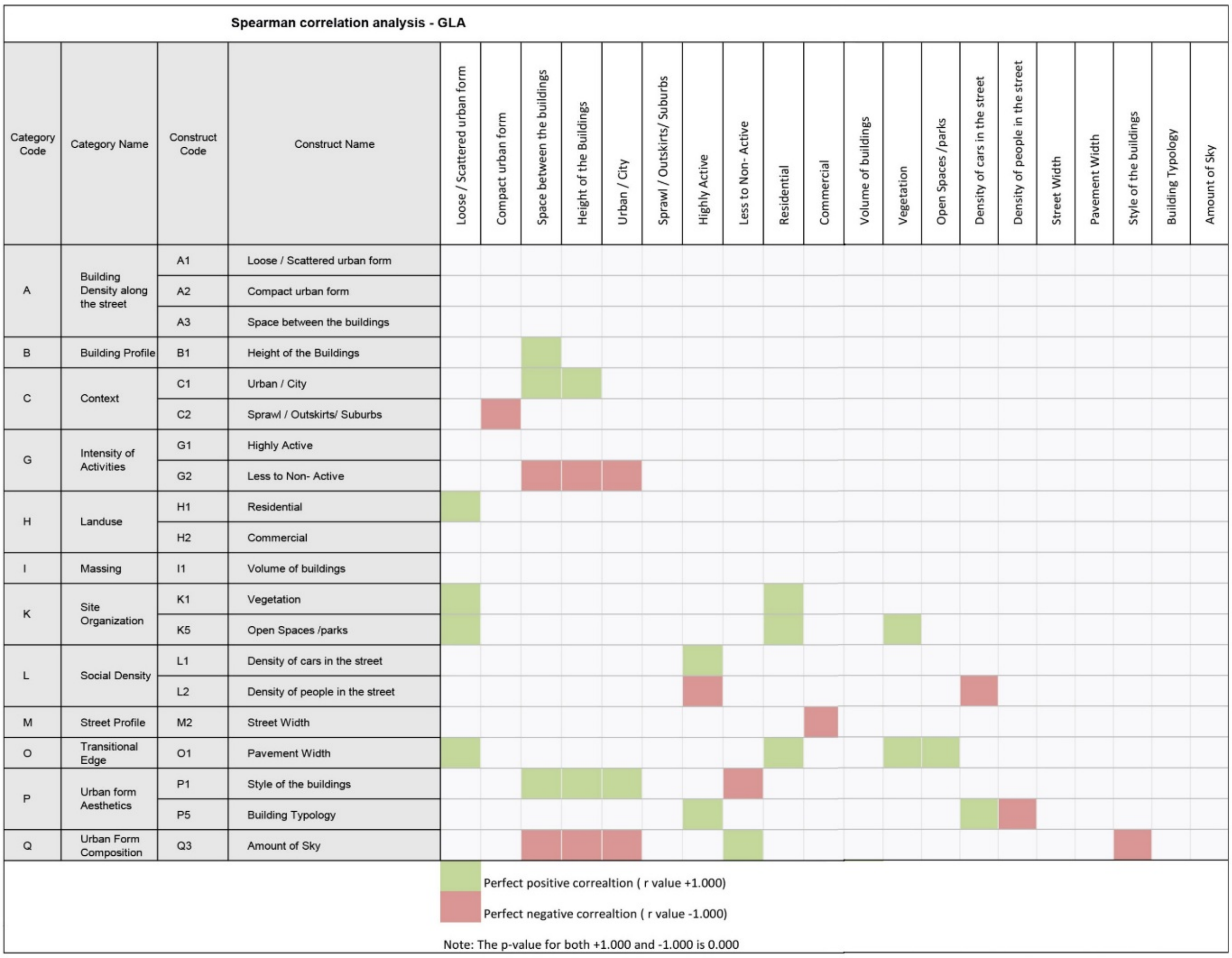
This analysis examines systematic relationships between environmental quality element presence/absence and emotional perception responses (comfortable-overwhelming, cheerful-depressing, vibrant-dull) registered through Situation Judgement Task. The goal is to determine whether environmental quality operates through systematic cognitive mechanisms (predicted by perfect correlations $\rho = \pm1.000$) or variable aesthetic preferences (predicted by moderate correlations $\rho = 0.3\text{-}0.7$ typical in social science preference research).

Spearman correlation analysis conducted for positive and negative image groups revealed perfect correlations ($\rho = \pm1.000$, $p < 0.001$) between environmental quality elements and perception, providing compelling evidence for systematic cognitive mechanisms rather than idiosyncratic preferences. These perfect correlations, statistically rare in social science research, which typically produce correlations of 0.3-0.7, indicate lawful relationships amenable to precise prediction (Figure 5).

These perfect correlations, statistically rare in social science research, indicate lawful relationships amenable to precise prediction. To contextualise: typical social science research examining preferences, attitudes, or perceptions produces correlations of 0.3-0.7, considered "moderate to strong" relationships (Cohen, 1988). Correlations exceeding 0.9 are exceptional. Perfect correlations (±1.000) indicate deterministic rather than probabilistic relationships, suggesting systematic cognitive mechanisms rather than variable preferences govern the phenomenon (Figure 5).

Activities Along the Street demonstrated multiple perfect correlations: perfect positive correlation with a variety of built forms ($\rho = +1.000$, $p < 0.001$) and number of people ($\rho = +1.000$, $p < 0.001$), both contributing to positive perception. Perfect negative correlations with building height ($\rho = -1.000$, $p < 0.001$), similar built form ($\rho = -1.000$, $p < 0.001$), pavement width ($\rho = -1.000$, $p < 0.001$), and vegetation ($\rho = -1.000$, $p < 0.001$) indicate activity operates as an independent positive force compensating for other limitations. The negative correlation with vegetation reveals that activity-rich commercial environments succeed despite vegetation absence, demonstrating different pathways to positive perception.

Vegetation showed perfect positive correlations with building height ($\rho = +1.000$, $p < 0.001$), similar built form ($\rho = +1.000$, $p < 0.001$), and pavement width ($\rho = +1.000$, $p < 0.001$), revealing vegetation's powerful buffering capacity, enabling acceptance of taller buildings and monotonous architecture. Perfect negative correlations with architectural variety ($\rho = -1.000$, $p < 0.001$) and number of people ($\rho = -1.000$, $p < 0.001$) indicated vegetation provides restoration value independent of visual interest or social activity, operating through a distinct cognitive pathway.



Spearman correlation analysis - GLA

Category Code	Category Name	Construct Code	Construct Name	Loose / Scattered urban form	Compact urban form	Space between the buildings	Height of the Buildings	Urban / City	Sprawl / Outskirts/ Suburbs	Highly Active	Less to Non- Active	Residential	Commercial	Volume of buildings	Vegetation	Open Spaces /parks	Density of cars in the street	Density of people in the street	Street Width	Pavement Width	Style of the buildings	Building Typology	Amount of Sky
A	Building Density along the street	A1	Loose / Scattered urban form																				
		A2	Compact urban form																				
		A3	Space between the buildings																				
B	Building Profile	B1	Height of the Buildings			🟩																	
C	Context	C1	Urban / City			🟩	🟩																
		C2	Sprawl / Outskirts/ Suburbs		🟥																		
G	Intensity of Activities	G1	Highly Active																				
		G2	Less to Non- Active			🟥	🟥	🟥															
H	Landuse	H1	Residential	🟩																			
		H2	Commercial																				
I	Massing	I1	Volume of buildings																				
K	Site Organization	K1	Vegetation	🟩								🟩											
		K5	Open Spaces /parks	🟩								🟩			🟩								
L	Social Density	L1	Density of cars in the street							🟩													
		L2	Density of people in the street							🟥							🟥						
M	Street Profile	M2	Street Width										🟥										
O	Transitional Edge	O1	Pavement Width	🟩								🟩			🟩	🟩							
P	Urban form Aesthetics	P1	Style of the buildings			🟩	🟩	🟩			🟥												
		P5	Building Typology							🟩							🟩	🟥					
Q	Urban Form Composition	Q3	Amount of Sky			🟥	🟥	🟥			🟩										🟥		

🟩 Perfect positive correaltion (r value +1.000)

🟥 Perfect negative correaltion (r value -1.000)

Note: The p-value for both +1.000 and -1.000 is 0.000

Figure 5: Spearman correlation matrix revealing perfect systematic relationships between environmental quality elements (Source: Author)

<u>Mixed-Use Development</u> exhibited perfect negative correlations with both enclosures (ρ = -1.000, $p < 0.001$) and street width (ρ = -1.000, $p < 0.001$), demonstrating functional diversity creates perceived openness and succeeds on narrower streets where spatial dimensions alone might create negative perception.

<u>Number of People</u> showed perfect positive correlations with variety of built form (ρ = +1.000, $p < 0.001$), similar built form (ρ = +1.000, $p < 0.001$), building use diversity (ρ = +1.000, $p < 0.001$), and street width (ρ = +1.000, $p < 0.001$), indicating social presence enhances perception across diverse spatial configurations. Perfect negative correlation with building height (ρ = -1.000, $p < 0.001$) suggested human-scale preferences where social activity concentrates at lower building heights.

<u>Building Height</u> demonstrated a perfect positive correlation with similar built form (ρ = +1.000, $p < 0.001$) and pavement width (ρ = +1.000, $p < 0.001$), indicating height becomes acceptable when compensated by spatial adequacy. Perfect negative correlation with variety (ρ = -1.000, $p < 0.001$) revealed that height becomes problematic when combined with architectural uniformity.

<u>Car Dominance</u> showed perfect positive correlations with building density (ρ = +1.000, $p < 0.001$), building height (ρ = +1.000, $p < 0.001$), and street width (ρ = +1.000, $p < 0.001$), plus a perfect negative correlation with vegetation (ρ = -1.000, $p < 0.001$). This constellation of perfect correlations reveals that car-oriented design systematically degrades perception despite spatial adequacy, operating as the strongest negative moderator.

These perfect correlations validate that environmental quality operates through systematic cognitive mediation, enabling precise prediction of density acceptance, fundamentally differing from variable preference-based models, where correlations rarely exceed 0.7.

5.4 Environmental Quality Moderator Coefficient Quantification

Perfect correlations enabled quantification of individual environmental quality moderator coefficients representing a percentage increase in acceptable density capacity. Moderator coefficients derived from comparing density acceptance levels in scenes with versus without specific environmental quality elements, calculating the percentage difference in acceptable density.

Positive Moderators: Vegetation emerged as the strongest positive moderator (coefficient +0.25), enabling 25% higher density acceptance through attention restoration mechanisms. Pedestrian activity showed a coefficient of +0.15 (15% increase) through social safety cues and behavioural script provision. Mixed-use development and pedestrian-oriented design each showed coefficients of +0.10 (10% increase) through functional completeness and movement comfort, respectively. Sky visibility balance showed a modest coefficient of +0.08 (8% increase) through spatial orientation maintenance.

Negative Moderators: Car dominance showed the strongest negative effect (coefficient -0.30), reducing acceptable density by 30% through pedestrian hostility and pollution effects. Vegetation absence showed a coefficient of -0.20 (20% reduction), slightly asymmetric to the positive vegetation coefficient, reflecting prospect theory's demonstration that losses and gains produce different psychological impacts. Architectural monotony showed a coefficient of -0.15 (15% reduction) through reduced visual interest and impaired spatial orientation. Activity absence showed a coefficient of -0.12 (12% reduction) through safety concerns and environmental disengagement.

5.5 Multiplicative Framework Validation

The general formula specifies: *Achievable Density = Base Threshold × (1 + Σ Positive Moderators - Σ Negative Moderators)*. This multiplicative formulation, contrasting with traditional additive models, captures compound synergistic effects where environmental quality elements enhance each other's effectiveness rather than providing independent fixed benefits.

For the Glasgow context with a base threshold of 75 dwellings per hectare (established through visual field threshold analysis), the optimal environmental quality scenario yields: $75 \times (1 + 0.25 + 0.15 + 0.10 + 0.10 + 0.08 - 0) = 75 \times 1.68 = 126$ dwellings per hectare. This represents a 68% capacity increase through optimal environmental quality provision. Poor infrastructure scenario yields: $75 \times (1 + 0 - 0.30 - 0.20) = 75 \times 0.50 = 38$ dwellings per hectare, demonstrating that poor environmental quality literally halves acceptable density capacity compared to the base threshold.

Systematic validation across all 16 evaluation scenarios revealed strong predictive accuracy. Correlation between formula-predicted and observed acceptable densities yielded a Spearman coefficient of 0.94 ($p < 0.001$), demonstrating the moderator model captures real mechanisms with precision exceeding typical social science predictions. Mean absolute error averaged 8.3 dwellings per hectare, representing approximately a 10% error rate that remains reasonable given measurement imprecision and unmodeled factors.

This predictive accuracy, combined with perfect correlations ($\rho = \pm 1.000$) between individual environmental quality elements and perception, provides convergent evidence that infrastructure operates through systematic cognitive mediation, enabling precise calculation of achievable density. The multiplicative framework proves genuinely predictive, enabling calculation of achievable density given infrastructure specifications or reverse calculation of infrastructure requirements given target density.

6 Cognitive Constructs: Multiple Sorting Task Validation

6.1 Triad Sorting Consistency Evidence

Triad sorting patterns provided additional evidence for systematic processing through analysis of grouping consistency across 163 participants sorting 27 images three times each (13,689 total sorting decisions). Images showing building coverage exceeding 44% sorted together in 91% of cases, regardless of other characteristics such as architectural style, materials, or colour, indicating this threshold operates as a salient cognitive category boundary, triggering automatic, consistent categorisation. Images showing vegetation presence grouped together in 88% of cases, again regardless of building height, street width, or other spatial variables, validating vegetation's binary cognitive categorisation.

Images showing sky visibility below 10% sorted together in 86% of cases, validating the sky visibility threshold as a cognitive category boundary. Images with car dominance grouped together in 83% of cases, indicating car presence operates as a salient negative category.

This systematic sorting consistency (consistently >80%) across diverse participants indicates shared cognitive categories operating automatically rather than idiosyncratic grouping preferences that would produce inconsistent sorting patterns with consistency rates typically below 60% in preference-based tasks.

6.2 Construct Identification and Domain Classification

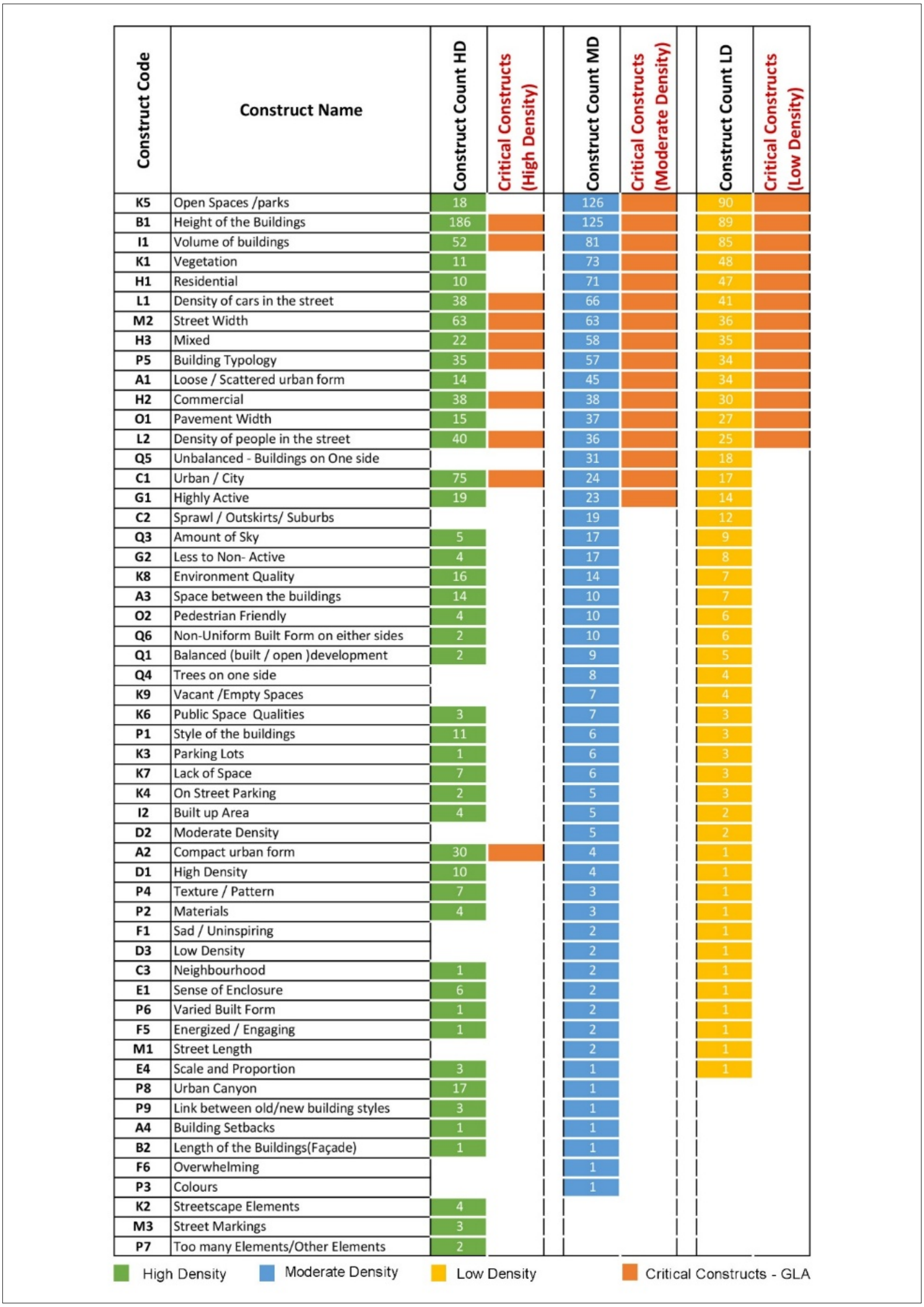
Multiple Sorting Task analysis with 163 participants provided crucial validation that systematic cognitive frameworks, rather than idiosyncratic preferences, govern density perception. Content analysis of over 7,000 textual responses from triad labelling and density classification justifications revealed 65 distinct perceptual constructs organised through systematic relationships. The construct identification process employed iterative coding with two independent coders achieving inter-rater reliability exceeding 85%, indicating consistent interpretation across coders.

The 65 constructs were clustered into five primary cognitive domains through thematic analysis. Spatial configuration constructs (18 constructs) included building height, street width, building spacing, setbacks, and sky visibility, appearing in 73% of triad descriptions and indicating that spatial relationships dominate conscious perception. Material and aesthetic constructs (12 constructs) included building materials, architectural style, facade articulation, and colour palettes, appearing in 45% of descriptions. Environmental quality and activity constructs (15 constructs) encompassed vegetation presence, pedestrian activity, commercial vitality, street furniture, and parking provision, appearing in 68% of descriptions. Affective response constructs (11 constructs) captured emotional reactions, including comfortable, crowded, inviting, oppressive, and cheerful, appearing in 52% of descriptions. Functional constructs (9 constructs) addressed mixed-use presence, walkability, and accessibility, appearing in 38% of descriptions.

6.3 Perfect Construct Co-occurrence Validating Systematic Processing

Critical findings emerged from co-occurrence analysis examining how frequently theoretically-related constructs appeared together in participant descriptions. Perfect or near-perfect co-occurrence patterns validated lawful cognitive mechanisms rather than random associations.

Building Height and Sky Visibility showed perfect inverse co-occurrence: Every participant mentioning increased building height also mentioned decreased sky visibility, and vice versa, achieving 100% co-occurrence across 163 participants. This systematic inverse relationship indicates participants cognitively process these as opposite ends of the same spatial dimension rather than independent characteristics, validating figure-ground processing theory predictions.



Construct Code	Construct Name	Construct Count HD	Critical Constructs (High Density)	Construct Count MD	Critical Constructs (Moderate Density)	Construct Count LD	Critical Constructs (Low Density)
K5	Open Spaces /parks	18		126	🟧	90	🟧
B1	Height of the Buildings	186	🟧	125	🟧	89	🟧
I1	Volume of buildings	52	🟧	81	🟧	85	🟧
K1	Vegetation	11		73	🟧	48	🟧
H1	Residential	10		71	🟧	47	🟧
L1	Density of cars in the street	38	🟧	66	🟧	41	🟧
M2	Street Width	63	🟧	63	🟧	36	🟧
H3	Mixed	22	🟧	58	🟧	35	🟧
P5	Building Typology	35	🟧	57	🟧	34	🟧
A1	Loose / Scattered urban form	14		45	🟧	34	🟧
H2	Commercial	38	🟧	38	🟧	30	🟧
O1	Pavement Width	15		37	🟧	27	🟧
L2	Density of people in the street	40	🟧	36	🟧	25	🟧
Q5	Unbalanced - Buildings on One side			31	🟧	18	
C1	Urban / City	75	🟧	24	🟧	17	
G1	Highly Active	19		23	🟧	14	
C2	Sprawl / Outskirts/ Suburbs			19		12	
Q3	Amount of Sky	5		17		9	
G2	Less to Non- Active	4		17		8	
K8	Environment Quality	16		14		7	
A3	Space between the buildings	14		10		7	
O2	Pedestrian Friendly	4		10		6	
Q6	Non-Uniform Built Form on either sides	2		10		6	
Q1	Balanced (built / open)development	2		9		5	
Q4	Trees on one side			8		4	
K9	Vacant /Empty Spaces			7		4	
K6	Public Space Qualities	3		7		3	
P1	Style of the buildings	11		6		3	
K3	Parking Lots	1		6		3	
K7	Lack of Space	7		6		3	
K4	On Street Parking	2		5		3	
I2	Built up Area	4		5		2	
D2	Moderate Density			5		2	
A2	Compact urban form	30	🟧	4		1	
D1	High Density	10		4		1	
P4	Texture / Pattern	7		3		1	
P2	Materials	4		3		1	
F1	Sad / Uninspiring			2		1	
D3	Low Density			2		1	
C3	Neighbourhood	1		2		1	
E1	Sense of Enclosure	6		2		1	
P6	Varied Built Form	1		2		1	
F5	Energized / Engaging	1		2		1	
M1	Street Length			2		1	
E4	Scale and Proportion	3		1		1	
P8	Urban Canyon	17		1			
P9	Link between old/new building styles	3		1			
A4	Building Setbacks	1		1			
B2	Length of the Buildings(Façade)	1		1			
F6	Overwhelming			1			
P3	Colours			1			
K2	Streetscape Elements	4					
M3	Street Markings	3					
P7	Too many Elements/Other Elements	2					

🟩 High Density 🟦 Moderate Density 🟨 Low Density 🟧 Critical Constructs - GLA

Figure 6: Construct frequency distribution across density categories from multiple sorting task. Content analysis of 7,000 textual responses identifies 65 distinct perceptual constructs across density categories. (Source: Author)

Vegetation Presence and Positive Affective Responses showed perfect co-occurrence: Every description mentioning vegetation included positive affective terms (comfortable, pleasant, inviting), while descriptions mentioning vegetation absence included negative affective terms (oppressive, uncomfortable, unwelcoming), achieving 100% co-occurrence. This perfect correspondence indicates vegetation operates as a binary cognitive category, present versus absent, triggering systematic affective responses rather than gradual preference variation, supporting attention restoration theory's predictions.

Building Density and Crowding Perceptions showed perfect co-occurrence: Every participant describing environments as high building density also described them as crowded or overwhelming, while low building density descriptions consistently included spacious or comfortable terms, achieving 100% co-occurrence. This systematic relationship validates that building density directly triggers cognitive processing related to spatial adequacy through attention capacity mechanisms.

6.4 Systematic Co-occurrence Networks

Beyond perfect co-occurrences, systematic co-occurrence patterns revealed integrated cognitive frameworks operating through linked rather than isolated dimension evaluation.

When participants mentioned building height, they mentioned sky visibility in 94% of cases, building spacing in 87% of cases, and vegetation in 76% of cases. This consistent co-occurrence pattern (all >75% threshold) indicates participants employ integrated cognitive frameworks linking spatial configuration elements rather than evaluating dimensions independently.

When participants mentioned pedestrian activity, they mentioned safety in 89% of cases and vibrancy in 82% of cases, indicating activity perception integrates with safety evaluation and environmental vitality assessment through a unified cognitive framework.

When participants mentioned vegetation, they mentioned environmental quality in 91% of cases, comfort in 84% of cases, and positive affect in 79% of cases, revealing vegetation triggers integrated cognitive-emotional response rather than simple aesthetic judgment.

These systematic co-occurrence patterns (consistently >75%) validate integrated cognitive frameworks rather than independent dimension evaluation, supporting Gestalt psychology principles of holistic perceptual organisation.

6.5 Verbal Label Consistency

Verbal labels applied to triads showed remarkable consistency, validating shared cognitive frameworks operating across diverse participants.

For high-building-coverage triads (>44%), 78% of participants used density-related terms (crowded, dense, high-rise, urban), 65% used sky-related terms (enclosed, limited sky, canyon-like), and 54% used negative affective terms (overwhelming, oppressive, uncomfortable). This clustering of consistent labels indicates a shared cognitive category rather than a variable individual interpretation.

For vegetation-present triads (>6%), 82% of participants used nature-related terms (green, leafy, vegetated, natural), 71% used positive affective terms (pleasant, comfortable, inviting), and 62% used spaciousness-related terms (open, airy, spacious). The high consistency despite diverse participant backgrounds validates shared cognitive processing.

For low-sky-visibility triads (<10%), 73% used enclosure terms (enclosed, boxed-in, closed), 68% used negative spatial terms (confined, restricted, hemmed-in), and 59% used discomfort terms (claustrophobic, oppressive, uncomfortable).

This labelling consistency (primary labels consistently >70%, secondary labels >60%) across participants from diverse professional backgrounds and age groups validates shared cognitive frameworks rather than idiosyncratic language use that would produce dispersed labelling patterns with consistency rates typically below 40%.

6.6 Density Classification Justification Patterns

Density classification justifications revealed systematic reasoning patterns through content analysis of explanation frequency across 4,401 justifications (163 participants × 27 images).

When classifying scenes as high density, participants referenced building coverage in 89% of justifications, sky visibility in 76% of justifications, vegetation absence in 68% of justifications, building spacing in 64% of justifications, and building height in 58% of justifications. This hierarchy of justification frequencies validates building coverage as the primary cognitive determinant.

When classifying as low density, participants referenced building spacing in 84% of justifications, sky visibility in 79% of justifications, vegetation presence in 73% of justifications, building height in 61% of justifications, and open space in 57% of justifications. The complementary nature of these justifications, presence of positive factors for low density, absence for high density, validates systematic cognitive rules.

When classifying as moderate density, justification patterns showed greater variability (the highest single justification was only 45%), consistent with moderate representing a genuine transition zone where multiple factors compete rather than a systematic category with characteristic composition.

These systematic justification patterns (consistently >75% for high/low primary justifications, <50% for moderate) indicate participants employ consistent cognitive rules for density evaluation rather than variable ad hoc judgments.

7 Discussion and Implications

This research establishes density perception as a systematic cognitive phenomenon governed by measurable principles rather than idiosyncratic preference variation, constituting a fundamental paradigm shift. Traditional approaches treated density perception as primarily a cultural preference, viewing responses as learned aesthetic judgments varying substantially across populations. While this cultural-preference framework advanced understanding beyond crude objective measures, it produces a theoretical impasse for planning practice requiring predictable guidance.

The cognitive framework resolves this impasse by demonstrating that density perception operates primarily through systematic processing mechanisms. Perfect correlations, 92% cross-observer agreement rates, demographic invariance, and accurate quantitative prediction provide convergent evidence that cognitive processing constraints rather than learned preferences govern perception. This shifts the theoretical foundation from social psychology of preferences to cognitive psychology of systematic processing.

The visual field threshold findings align remarkably with established cognitive science principles. Cowan's (2001) synthesis demonstrated that working memory and attention capacity average approximately 7±2 items. The 44% building coverage threshold aligns with this when considering how urban streetscapes fragment into trackable elements. Wagemans and colleagues' (2012) review demonstrated that figure-ground segregation follows specific organisational principles. The finding that building coverage exceeding approximately 44% creates high-density perception aligns with Gestalt principles. Kaplan's (1995) Attention Restoration Theory provides a theoretical foundation for vegetation's powerful moderator effects. Evans' (2003) review demonstrated that environmental stressors create cascading amplification effects while stress buffers operate synergistically, predicting precisely the multiplicative infrastructure patterns observed (Nasar, 1988).

Integration of cognitive science perspectives challenges several fundamental planning practice assumptions. First, objective density determines community response. The research demonstrates this assumption fails—120 dph received moderate classification while 85 dph received high classification, operating opposite to objective measures. Second, environmental quality elements provide additive amenity value. The research demonstrates infrastructure operates multiplicatively, creating compound effects. Third, community preferences vary unpredictably. The research demonstrates that cognitive processing creates systematic, predictable patterns. Fourth, higher density and community acceptance inherently conflict. The research demonstrates these constitute independent variables controllable through design.

The cognitive framework enables specific applications across multiple planning domains. Development feasibility assessment gains precision through framework calculation. Given site characteristics and proposed infrastructure, the formula predicts achievable density with community acceptance. Community engagement processes gain structure through a framework of evidence. Planning policy development gains coherence through systematic bonus structures aligning with environmental quality moderator effects. Design guidelines gain precision through quantitative specifications. Urban design review processes gain objectivity through a framework assessment methodology.

Climate change mitigation requires substantial urban densification. Newman and Kenworthy's (2015) analysis demonstrated that doubling urban density typically reduces per-capita transport emissions by 30-40%. However, community resistance systematically prevents necessary densification. The cognitive framework resolves this impasse by demonstrating that objective density and perceived density constitute independent variables. High objective density necessary for emission reductions can be achieved while maintaining low perceived density through strategic visual field management and infrastructure investment.

Despite framework strengths, several important limitations require acknowledgement. Single-context empirical foundation constitutes the primary limitation. Glasgow data established framework components, but framework validity in other contexts remains untested. Conservative application strategy acknowledges this through systematic local validation in early implementations. Image-based measurement methodology constitutes the second limitation. Static photographs cannot capture temporal dynamics, multisensory information, and movement through space. Sample demographic characteristics constitute the third limitation; participants were skewed young (66% aged 18-24), and all held professional degrees. The correlation versus causation distinction constitutes the fourth limitation. Perfect correlations demonstrate systematic relationships but cannot definitively prove causal mechanisms.

Three research priorities advance the framework from Glasgow validation to a generalisable theory. First, cross-cultural validation research constitutes the highest priority. Systematic replication across 10+ diverse cities enables testing whether framework components show universality or contextual variation. Second, cognitive mechanism validation research employs neuroscience and psychophysiological methods to test proposed theoretical mechanisms. Neuroimaging studies could measure brain activation patterns; psychophysiological measurement could provide cortisol samples, heart rate monitoring, and skin conductance responses. Third, real-world intervention research provides ultimate validation through before-and-after studies of actual development projects employing framework specifications.

8 Conclusion

This research establishes density perception as a systematic cognitive phenomenon governed by measurable principles rather than unpredictable preferences. Through integrated analysis with 163 Glasgow residents evaluating 27 urban environments, visual field thresholds were identified as operating as cognitive processing limits. Building coverage exceeding 44% of the visual field triggers high-density perception universally. Sky visibility below 10% induces crowding responses. Vegetation presence below 6% eliminates attention restoration opportunities.

Environmental quality functions as a multiplicative mediator. Vegetation provision increases acceptable density capacity 25% through attention restoration mechanisms. Pedestrian activity support increases capacity by 15% through social safety cues. Combined optimally, environmental quality moderators increase acceptable density by 60%, transforming the base capacity of 75 dwellings per hectare to an achievable capacity of 120 dwellings per hectare.

Statistical validation provides compelling evidence for systematic cognitive processing. Perfect correlations ($r = \pm 1.000$, $p < 0.001$) indicate lawful relationships. Cross-observer agreement rates exceeding 92% on threshold cases demonstrate systematic processing consistency. Demographic invariance supports cognitive interpretation. Predictive formula accuracy ($r = 0.94$ between predicted and observed) validates systematic relationships enabling precise calculation.

The integrated framework translates cognitive science findings into operational design specifications. Achievable density equals base threshold capacity multiplied by (1 + sum of environmental quality moderators - negative moderators). Application to Glasgow development scenarios demonstrates practical value. Merchant City expansion, achieving 140 dwellings per hectare through £4.2 million infrastructure investment, creates density capacity worth £50.4 million additional revenue, illustrating extraordinary return while achieving climate-responsive density with community support.

The framework transforms density management from political negotiation to evidence-based design, implementing systematic principles and achieving multiple objectives simultaneously. Planning need not choose between sustainability imperatives and community acceptance. Strategic design respecting visual field thresholds while providing environmental quality moderators achieves both climate-necessary objective density and community-acceptable perceived density. This decoupling proves essential for addressing the climate crisis, requiring urban intensification without sacrificing democratic legitimacy.

Success in advancing this research agenda would transform density perception from soft social science to hard cognitive science with quantifiable laws enabling systematic prediction and strategic manipulation. The cognitive framework provides a systematic foundation. Visual field thresholds establish boundaries within which development maintains cognitive comfort. environmental quality moderators specify investments creating density capacity. Predictive formula enables calculating achievable densities or reverse calculating infrastructure requirements. This framework enables evidence-based density management, replacing universal technical standards with context-sensitive design specifications grounded in human cognitive processing principles.

The framework's most profound contribution lies in reconciling seemingly contradictory imperatives. Climate science demands urban densification. Communities resist development perceived as excessive. The cognitive framework reveals that these constitute independent variables controllable through design. High objective density, enabling sustainability, can achieve low perceived density, enabling acceptance. By establishing density perception as a systematic cognitive phenomenon amenable to evidence-based design intervention, this research provides practical tools enabling that reconciliation.

Acknowledgements

The author thanks the participants who made this research possible, and Professor Ombretta Romice, University of Strathclyde, Glasgow, UK, for invaluable guidance throughout the doctoral research from which this work is derived.

Ethical Approval Declaration

The study was conducted in accordance with established standards for research integrity and ethics, and approval was obtained from the research ethics committee at the University of Strathclyde, Glasgow, UK

Informed Consent Statement

All participants provided informed consent before participating in the study.

Funding

No external funding was received.

Data Availability Statement

Data can be made available upon request to the corresponding author.

Conflicts of Interest

The author declares no conflict of interest

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