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An Empirically Validated Framework for Investigating the Perception of Density

Abstract

Purpose- In urban studies, understanding how individuals perceive density is a complex challenge due to the subjective nature of this perception, which is influenced by socio-cultural, personal, and environmental factors. This study addresses these complexities by proposing a systematic framework for comprehending how people perceive density within urban contexts.

Design/ methodology/approach- The methodology for developing the framework involved a systematic review of existing literature on the perception of density and related concepts, followed by integrating insights from empirical investigations. The framework designed through this process overcomes the limitations identified in previous research and provides a comprehensive guide for studying perceived density in urban environments.

Findings- The successful application of the framework on case studies in Glasgow and international settings enabled the identification of 20 critical spatial factors (buildings, public realm and urban massing) influencing density perception. The research provided insights into the subjective nature of density perception and the impact that spatial characters of urban form play, demonstrating the framework's effectiveness in understanding the impact of urban form, which is the realm of design and planning professions, on individual experiences.

Originality - The paper's originality lies in its comprehensive synthesis of the existing knowledge on the perception of density, the development of a user-responsive framework adaptable to future research, and its application in case studies of different natures, to identify recurrent links between urban form and user-specific constructs.

Article Classification- Research paper

Keywords- Perception, Density, Urban Environment, Framework, Image analysis, Perceived Density

1. Introduction

The concept of urban density is often seen as a technical term that quantifies the number of participants or buildings per unit area in a neighbourhood (Berghauser Pont *et al.*, 2021; Berghauser Pont and Haupt, 2009; Cheng, 2010a, 2010b; Churchman, 1999; DETR, 1998a; Rapoport, 1975; Sonne, 2017). It is commonly used in land use regulation and significantly impacts the characteristics and functionality of urban environments. These macro-level approaches focus on density's technical and economic aspects, such as spatial configuration and access to amenities, but do not capture appearance, feel, or perception (Berghauser Pont et al., 2010, 2021; Campoli & Maclean, 2002). Hence, recent studies are increasingly accompanied by micro-level work to consider the (often adverse) effects of density and examine the perceptual and cognitive elements that shape human experiences of the built environment (Halasz, 2015). This paper aims to bridge the gap between these two approaches and develop a comprehensive method to study how density is perceived concerning spatial characters of urban form to inform design towards delivering well-perceived density.

Perceived density, a term introduced by Rapoport (1975), considers an individual's perception of (primarily outdoor) space, its organisation, and the estimation of the number of people in a given area (Churchman, 1999; Rapoport, 1975). Rapoport (1975) emphasised that density is a subjective experience influenced by various factors such as the spatial attributes of the built environment, social interaction, and personal characteristics. Expanding on Rapoport's concept, *perceived density* was defined further as the interaction between three elements: physical density (including measured density), individual cognitive factors, and sociocultural factors (Alexander, 1993). These definitions of perceived density encompass a combination of social and spatial density (Altman, 1975; Loo, 1990; Loo and Kennelly, 1979) or a mix of objective density, built form, and sociocultural elements. They deal with concepts such as perception of space (Brown, 2001; Sommer, 1969; Tuan, 1977) and sociocultural factors (Alexander, 1993; Evans *et al.*, 2000; Rapoport, 1975), which are dealt with by independent fields of study. Whilst these studies are rich, they are also often context, subject or conditions specific (Bergdoll and Williams, 1990; Cheng, 2010b; Emo *et al.*, 2017; Fisher-Gewirtzman, 2018; Flachsbart, 1979; Lilli, 2013), creating issues in any attempt to generalise findings.

Perceived density has gained significant attention in urban design and cognitive psychology due to concerns about the perceived comfort of individuals in high-density developments (Cheng, 2010b). While high-density developments are increasingly necessary for matters of sustainability and efficiency (Bramley and Power, 2009; Dempsey *et al.*, 2012), they often negatively impact the quality of life of those experiencing them, thus undermining, at least on experiential levels, their more practical positive effects (Loo, 1990; Saegert, 1979; Winsborough, 1965). Despite various design attempts to address these consequences, the problem persists. This study explores how people experience density in urban environments and uses this understanding to gain insight into how to tackle spatial characters of urban form to maintain the benefits of its higher density values while minimising its negative perceptions. It relies on the psychological framework of personal construct theory (Kelly and Kelly, 2017) to understand how individuals mentally construct and interpret their experiences of the urban environment and to what extent these relate to perceived density.

Recent advancements in the study of perceived density recognise vision as the key means through which density is experienced and employ techniques such as immersive virtual reality environments or real-time data to determine the role of spatial factors in enhancing or mitigating its impact. For example, the Spatial Openness Index (SOI) evaluates the spatial arrangement of urban environments in controlled immersive three-dimensional laboratory environments based on visibility from a reference location (Fisher-Gewirtzman, 2003, 2017, 2018; Fisher-Gewirtzman *et al.*, 2003; Fisher-Gewirtzman and Wagner, 2003). Along similar lines, the sky view factor (Cheng, 2010b) assesses the proportion of visible sky in the surrounding built environment using Digital Elevation Modelling (DEM) and environmental simulation. Another study established an association between spaciousness and perceived density using Discreet Choice Modelling (DCM) (Lilli, 2013). These methods offer valuable perspectives on human perception of density. However, they have limitations, including issues with their replicability, findings linked to specific contexts, resolution of images, accuracy of data collection and simplification, ensuring data precision and the reduction of complex phenomena into manageable variables. Integrating multiple approaches and validating findings through real-world observations represented by coloured photos compared to sketches, 3D visualisations, or drawings can help overcome these limitations and provide a more comprehensive understanding of how density is perceived.

2. Objective Density and Perceived Density Measures

The most common density measures are of two types: population density and building density. *Population density* is generally defined as the number of people occupying an area, whereas *building density* is defined as the number of buildings occupying an area (Cheng, 2010a). Many follow these definitions since they can be extended to different geographical domains such as neighbourhoods, towns, cities, and regions.

Both of these measures help characterise the performance of urban settings and their contribution to achieving sustainable goals in urban planning (Cervero and Bosselmann, 1994; Dempsey *et al.*, 2012). For example, environmental studies use density measures to estimate greenhouse gas emissions, the urban heat island effect, and its consequences for biodiversity (DETR, 1998a, 1998b). In economics, density indicators are frequently correlated with economic variables like house prices and development costs (Alexander, 1993; DETR, 1998a, 1998b; Oliveira, 2021). In environmental psychology, these metrics study the relationship between physical space and human behaviour on crowding, privacy, territoriality, and personal freedom (Altman, 1975; Stokols *et al.*, 1987; Taylor and Stough, 1978). In human sociology, numerical density is related to well-being, social interaction, social equity, and crime rates (Berghauser Pont *et al.*, 2021; Saegert, 1979; Winsborough, 1965). Nonetheless, these measures only partially account for the user's perception of density, which could inform the design of a user-friendly urban form.

Perceived density cannot be expressed through an objective metric but through various indicators that describe the subjective experience of space. For instance, crowding evaluates how much individuals perceive the space as visually crowded or congested (Edney, 1977; Freedman, 1975; Loo, 1975; Mueller, 1981; Saegert, 1973; Stokols, 1976). Perceived occupancy involves subjective assessments of the perceived occupancy level or the number of people perceived to be present in a defined space (Cheng, 2010b). Spatial enclosure evaluates the degree to which individuals perceive the space as enclosed based on its spatial characteristics, such as building height and setbacks

(Halasz, 2015; Loo, 1972; Novelli, 2010). Perceived privacy relates to the individual's subjective assessment of privacy in a given area (Altman, 1975; Namazian and Mehdipour, 2013). Sensory stimuli (light and colours, sound and noises, scents and odours, temperature variations) focus on an individual's sensory experiences within a space and how they relate to the perception of density (Boy, 2021; Milgram, 1970).

While these measures of perceived density provide valuable insights into an individual's subjective experiences, they have limitations. Perceived density measures rely heavily on individuals' perceptions and interpretations, which are by nature variable and biased (Mcleod, 2023; Taylor, 1981). Subjectivity makes it challenging to establish a standardised or objective measure of perceived density (Cheng, 2010b; Weber, 2003). Moreover, social and cultural factors also influence the perception of density (Carp, 1997; Evans *et al.*, 2000), making any comprehensive account of perceived density challenging, as they are complex and context-dependent. As a result, existing perceived density indicators are context-specific and cannot be easily generalised across different environments or populations.

This study addresses these limitations of perceived density measures by focusing on urban form, encompassing the spatial structure and arrangement of buildings, streets, and public spaces in urban areas (Dempsey *et al.*, 2010; Oliveira, 2016; Rapoport, 1977). Capturing all complexities associated with individual perceptions is essential for a comprehensive understanding of perceived density and promoting inclusive, sustainable urban development, necessitating a holistic approach combining urban form and individual perspectives.

2.1. Approach to Understanding Perceived Density

Rapoport's (1975) work serves as the foundation for this research and has influenced numerous subsequent studies that aimed to develop a comprehensive approach to understanding perceived density. He put in place a comprehensive framework that primarily differentiated between measured density and perceived density and examined various hypothesised variables (factors/cues) associated with the perception of density. The framework suggests that people use a variety of visual and perceptual cues to make sense of and form judgments about their surroundings. These cues help individuals navigate and understand their environment by providing cues or signals that convey specific meanings, associations, and emotions.

Rapoport's framework classifies these cues into three main categories:

1. Perceptual Cues: These cues pertain to how individuals perceive the physical attributes of the environment. They involve visual elements like colours, textures, shapes, and patterns that contribute to people's understanding of spatial relationships, dimensions, and proportions. Perceptual cues help individuals judge objects' depth, size, and position in their environment.

2. Symbolic/Associational Cues: These cues encompass visual or non-visual elements that carry symbolic meanings or associations. They include elements representing or communicating specific ideas, concepts, cultural values, or historical references. For example, architectural styles, street art, landmarks, and public spaces can evoke specific cultural or historical associations and communicate a particular sense of place.

3. Temporal Cues: Temporal cues relate to elements that change over time and influence people's perception of the environment. These cues can include factors like traffic patterns, pedestrian footfall at different times of the day, and changes in lighting. Temporal cues contribute to the dynamic and ever-evolving nature of how people experience and interpret their surroundings.

Rapoport’s framework serves to pinpoint and comprehend the variables that shape the perception of density and facilitate the distinction between diverse urban contexts. For example, within this framework, perceptual cues directly relate to the perceived compactness or spaciousness and the heightened presence of elements such as enclosures, streetscape attributes, pedestrians, or vehicles. In contrast, symbolic cues encompass the concrete characteristics of the environment, encompassing factors like building height, architectural style, and the abundance of foliage or green spaces. Given the continuous transformation of the urban landscape through varying rhythms and activity levels, the temporal dimension is also integral.

The framework's effectiveness can also be illustrated through an urban form context: within a high-density environment, perceptual cues might translate into tightly clustered structures, bustling streets, and a sense of enclosure due to verticality. Symbolic cues could manifest as numerous towering skyscrapers, while temporal aspects might include a dynamic flow of pedestrian activity throughout the day. On the other hand, in a low-density context, perceptual cues evoke a sense of openness and tranquillity, symbolised by fewer buildings and more green spaces. This hypothesised system of cues has been tested in partial contexts, and its comprehensive validation is a vital focus of this study. The next section explores empirical studies that reflect Rapoport's approach partially, which suggest that the perceptual cues significantly influence our understanding of density within urban environments. This understanding sets the stage for a comprehensive validation of the hypothesized system of cues, a vital focus of this study, which will be discussed in the subsequent sections.

2.2. Empirical Insights: Rapoport's Approach to Perceived Density

Seven studies have examined the concept of perceived density focusing on the spatial layouts of residential settings (Beck *et al.*, 1987; Flachsbart, 1979), visibility (Emo *et al.*, 2017; Norcross, 1974) and visual complexity (Bergdoll & Williams, 1990) of the built form along the streets; the built form, elements of non-built form and concept of spaciousness (Cheng, 2010b; Lilli, 2013). The summary of the findings is described in (*Table I)*.

Norcross (1974) explored how the location, orientation, and views from dwelling units within residential layouts impact density perception. The study found that the placement and orientation of dwelling units and the views they offered influenced residents' perception of density. Natural views, such as green spaces or parks, were associated with a lower perception of density. Zehner and Marans (1973) compared moderate-density townhouses and conventional detached single-family neighbourhoods, considering aspects of residential life and overall liveability. They found that lower housing costs and improved access to facilities positively influenced perceived density in townhouse neighbourhoods. Factors like neighbourhood maintenance, play areas, and overall attractiveness also shaped the perception of density. Flachsbart (1979) investigated a range of housing layouts and discovered that block length, street intersections, and population density significantly contributed to how people perceive density within their residential neighbourhoods. Bergdoll Williams (1990) studied the impact of physical attributes on density perception, highlighting factors such as building articulation, architectural details, materials, open spaces, and the presence of trees. These elements influenced how individuals perceived congestion levels and density in residential neighbourhoods. Cheng (2010b) examined both built (building height, street attributes) and non-built factors (people, streetscape elements) that affect density perception. Sky view and ground openness contributed to spaciousness, while non-built factors like vehicular activity also shaped perceived density. Lilli (2013) explored the role of spaciousness and openness in density perception, finding that factors like trees, setbacks, and broader streets mitigated the effects of high-density dwelling types. Emo et al. (2017) highlighted the significance of visibility in density perception. The number of visible buildings and green spaces were identified as crucial factors shaping individuals' perception of urban density. These studies provide insights into how multifaceted factors influence the perception of density in urban environments.

These prior studies serve as empirical evidence that can help verify the relevance and applicability of Rapoport's framework in diverse urban contexts. By examining how the cues proposed by Rapoport align with findings from subsequent research, the current study can strengthen its arguments and conclusions about the factors influencing density perception. This process of cross-referencing with prior studies not only lends credibility to the identified cues but also provides a broader context for interpreting the results concerning the broader body of urban perception research.

Categories	Factors Influencing Perceived Density	Author (Year
Morphology / Layout	Block Sizes (Length/ Width/Shape)	Flachsbart (1979)
	Street Width / Profile (Shape Slope)	Flachsbart (1979); Cheng (2010)
	Space Between the Houses	Beck, Bressi & Early (1987); Bergdoll & Williams (1987)
	Setbacks	Beck, Bressi & Early (1987);

		Lilli (2013
	Number of Buildings	Emo (2017)
Visibility	Views and Vistas	Beck, Bressi & Early (1987);
	Visible Open Space	Cheng (2010)
	Sky View	Cheng (2010)
Vegetation	Vegetation Along the Street	Beck, Bressi & Early (1987);
	Tree Coverage	Lilli (2013)
	Visible Green	Emo (2017)
Built Form Characteristics / Façade Articulation	Architectural Style	Beck, Bressi & Early (1987);
	Taller Buildings	Bergdoll & Williams (1987)
	Building Heights	Cheng (2010; Emo (2017)
	Less Façade Area / Smaller Buildings	Bergdoll & Williams (1987)
	A large number of Windows	Bergdoll & Williams (1987)

Table I. Summary of findings of prior empirical studies on perceived density

2.3. Methodological Insights: Challenges and Limitations in Previous Perceived Density Studies

Most perception studies use interviews, questionnaires, and photographic simulations to elicit respondent views. Questionnaires generally consist of binary (yes-or-no) questions or rating urban environments presented in images using a Likert scale. In contrast, interviews consist of open-ended questions to elicit the respondents' experiences. Although binary questions are straightforward and assist in coding the findings, the responder may have differing views on the alternatives presented and may feel hesitant or coerced into selecting one. As the objective of empirical studies is to capture the user's perspective, interviews are often favoured, even though they can be time-consuming, provide less anonymity, and could create a bias (Bailey, 1994). Interviews completed by visual surveys allow researchers to explore subjective aspects of perception, including emotions, thoughts and sensory experiences.

Visual surveys involve different kinds of photographic simulation (line diagrams, photographic elevations, street perspectives, and panoramas), which have proven to be an effective method for investigating the perception of urban landscapes (Bergdoll and Williams, 1990b; Cheng, 2010a; Emo *et al.*, 2017b; Lilli, 2013b). They are engaging, elicit precise and spontaneous responses, and often can have an edge on ordinary verbal questions as they can avoid verbal barriers. Photographic simulation as a stand-alone method, though, may limit the practical description of an event (Cheng, 2010a); hence, they are typically accompanied by a field survey (Bergdoll and Williams, 1990b; Cheng, 2010a), interviews, or questionnaires (Emo *et al.*, 2017b), or scaling questions define (Bergdoll and Williams, 1990b; Flachsbart, 1979). Recent research (Lilli, 2013b) used Discrete Choice Modelling (DCM), a technique used in market research, in conjunction with photographic simulation to collect unbiased information from respondents.

Both verbal and visual surveys can have limitations: they are inherently subjective. They rely on individuals' interpretations, opinions, and feelings, which can vary widely from person to person. Participants may need more context to understand the situation or environment presented in visual surveys, such as photographs or diagrams. Both verbal and visual surveys simplify complex experiences or situations into discrete responses or images, potentially oversimplifying the richness of real-life experiences. Furthermore, focusing on specific variables and contexts, using fewer case studies or photographs, and relying on existing data without real-time validation. These limitations restrict the generalizability of the findings and highlight the need for more comprehensive and diverse study designs with larger sample sizes and varied stimuli to enhance the reliability and applicability of the research. These challenges underscore the importance of developing a more robust and versatile framework for studying perceived density that can overcome these issues discussed in the following section.

3. Addressing Methodological Constraints in Density Perception Studies

Mapping the contents of perception is methodologically challenging due to the subjective qualities of experience, defying a singular ideal decoding method (Démuth, 2013; Stufflebeam, 2003; Whyte, 1985). Because every method has limitations, utilising the knowledge gained from the shortcomings of earlier methods makes it possible to develop a more reliable and applicable system for mapping human perception. The proposed system involves the framework, methodological approach, application and case study.

Introducing the Framework

The framework includes all the essential components for studying perceived density. A systematic literature review incorporates previous study findings while addressing their limitations. This framework includes scale, settings, street selection, and data collection methods. The street selection methods in this study use GIS and quantitative methods like Multiple Centrality Assessment (Porta et al., 2008) and Urban Morphometrics (Fleischmann, 2019), still Space Syntax and Density-Based Clustering can be used depending on the research objective.

The framework uses Personal Construct Theory to design the Multiple Sorting Task data collection method for the first survey (Kelly and Kelly, 2017). This theory helps researchers understand how people categorise their environment based on their perspectives and constructs. The survey design, executed through a triad setup, allows participants to sort images by content similarity to express their subjective opinions. Participants classified 27 images as low, moderate, or high density and curated them into nine triads. This meticulous survey covered a range of density levels in Glasgow's urban environments.

Universal illustrations added context for a better understanding. The Situation Judgment Task used 16 images to assess participants' opinions of the urban environment. The Multiple Sorting Task had participants categorise and sort images of urban environments with different density levels to reveal the underlying factors that shape their perceptions of density, while the Situation Judgment Task examined participants' comprehensive evaluation of the perceived value and multi-dimensional aspects of urban environments, focusing on density interpretation.

Analysis of both image sets involves systematic image segmentation. This crucial step revealed quantitative thresholds for eight key visual components and enabled Gestalt theory-based density perception interpretation. The Gestalt analysis used proximity, similarity, closure, and figure-ground relationships to determine how these affect urban density perception. This integrated approach improved understanding of how these fundamental visual attributes affect density perception in urban settings and helped develop a comprehensive visual assessment index for evaluating urban environments using images, which will be discussed in future papers.

3.1. Articulating the Framework

Framework identifies the critical components and considerations for studying perceived density. It was derived through a systematic literature review on perceived density, urban form and related concepts. The framework also considers previous studies' limitations and aims to provide a more comprehensive approach to understanding perceived density. The framework is designed to achieve two research objectives:

1. To identify and expand the list of factors (perceptual, symbolic, and temporal) influencing the perception of density using an open-ended questionnaire, reducing researcher bias by avoiding predetermined characteristics.
2. To quantify the impact of visual components associated with low, moderate, and high density through image analysis.

The framework incorporates various elements, including scale, settings, street selection, photographic simulation, sample size determination, survey type, and participant selection. The framework emphasises the importance of diverse urban environments, varied stimuli, and real-time data collection to enhance the reliability and generalizability of the research findings. This framework was developed and tested using the following eight conditions:

Scale: This framework emphasises the significance of the pedestrian scale, as it allows individuals to engage with the urban environment. Walking at a speed of 5km per hour, pedestrians can immerse themselves in the architectural details and sensory experiences that contribute to the perception of density (Gehl *et al.*, 2016; Nasar, 1989). By focusing on the pedestrian scale, this study aims to capture the nuances and intricacies of how density is perceived at the level of individual human experience.

Settings: It is essential to select streets that represent a diverse range of uses, including both homogeneous (residential or commercial) and heterogeneous (mixed-use) settings. These streets should provide perceptual, symbolic, and temporal cues contributing to the overall density perception. In the context of this study, the city of Glasgow serves as the location for selecting mixed-use streets. However, it is essential to note that this concept can be applied to any location, emphasising the importance of capturing various types of urban environments to comprehensively understand the perception of density.

Method for Street Selection: A systematic method is employed to select streets that ensure maximum comparability. This method involves identifying built forms with similar objective density along the street, considering their urban centrality position within the street network of the city, and selecting streets with similar uses but distinct urban forms. Geographic Information System (GIS), Google Earth Imagery, and field observations are utilised. Two specific quantitative methods, namely Multiple Centrality Assessment (Porta et al., 2013) and Urban Morphometrics (Fleischmann, 2021), are employed as GIS applications to facilitate the selection of streets in Glasgow. Based on the research objectives, other quantitative methods such as Space Syntax ((Hillier and Hanson, 1989), Density-Based Clustering (Campello *et al.*, 2013; Ester *et al.*, 1996), and so on can be applied.

Photographic Simulation Selection: In order to capture the real-life scenario, a photographic simulation such as coloured photographs of the streets is considered as an alternative (Snow *et al.*, 2014; Stewart *et al.*, 1984), which also eliminates the factor of mobility (moving people and vehicles). These photographs should represent street perspectives captured from the sidewalk, which align with the actual corridors of pedestrian movement. It is essential to only use photographs taken from the centre of the street if it is a designated pedestrian street.

Number of Case examples: For comprehensive findings, perception experiments utilising photographic simulation should include a minimum of 15 to 25 images (Canter et al., 1985; Chollet et al., 2014). In the context of this study, the first survey, a multiple sorting task, employed the triads (group of three) approach to sort the images based on the similarity of the content, so the total number of images used was 27, resulting in 9 triads. For the second survey, the situation judgment task, 16 images were used.

Sample Size: Determining the sample size for a survey on perception studies depends on several factors, including the research objectives, the desired level of precision, and the population being studied. While there is no one-size-fits-all approach, some general guidelines can be considered. In the context of this study, the target sample size was set to be between 100 and 200 respondents. However, approximately 163 responses for the case study conducted in Glasgow were obtained.

Survey Type: To facilitate the expression of individual experiences, the survey should consist of open-ended questions allowing respondents to freely share their perceptions (verbally or in writing). It could be a single survey or a collection of surveys to accomplish multiple objectives. Single or multiple surveys may be employed depending on the research objectives. In this study, two small and interactive surveys were developed based on the multiple sorting task and the situation judgment task to identify the factors influencing the perception of density and to determine the perceived value of the urban environment.

Participant Type: The surveys can provide insights into individual conceptual systems and opinion variations between different participant groups, such as laypeople and experts. Participants aged 18 to over 65 were included in this study, representing diverse backgrounds, including laypeople, architectural students, and design and planning professionals.

3.2. Operationalising the Framework

In the systematic implementation of each condition step within the framework, methodological decisions were carefully undertaken, encompassing the initiation of a Systematic Literature Review (SLR), site selection, data collection techniques, and data analysis approaches. To begin with site selection, streets were identified as an optimal context for this research due to their significant role as the primary environments of human experience. The process of street selection encompassed two key phases: firstly, the application of a Geographic Information System (GIS), Multiple Centrality Assessment (Porta et al., 2006), and Urban Morphometrics (Fleischmann, 2019)

alongside on-site field observations to identify streets that share similar objective densities while showcasing distinct urban configurations.
A dual-pronged strategy was employed in data collection, consisting of the Multiple Sorting Task (Canter, 1996) and the Situation Judgment Task (Wolcott et al., 2020). These methodologies facilitated the collection of rich insights into participants' perceptions and preferences about density and urban environments. Following the data collection phase, the raw survey data underwent meticulous analysis. The data processing and interpretation encompassed the adoption of content analysis (Kleinheksel et al., 2020) for the textual responses and image analysis techniques (Debals and Brabandere, 2020; Hook and Glaveanu, 2013) for the images themselves. Through these analytical tools, researchers were adept at extracting meaningful patterns and trends from the survey responses and images, yielding significant conclusions and insights contributing to the study's overarching goals.

Street Selection: This study recognises the need to consider streets with diverse built forms and different intensities of activities for three reasons: diverse built forms can assist in capturing different visual cues and spatial configurations; they contribute to visual complexity; they influence diverse activities and their intensity. Therefore, to ensure that the study sample represents the complexity and variability of real-world urban settings, leading to more robust and meaningful findings, this study proposes a street selection method involving Multiple Centrality Assessment (MCA) (Porta *et al.*, 2006), Urban Morphometrics (UMM)(Fleischmann, 2019) and field observations.

In the context of urban streets, the concept of centrality used in network analysis identifies the streets that play a crucial role in connecting different parts of the city, facilitating movement and accessibility (Porta et al., 2008, 2013). Three centrality measures, straightness centrality, closeness centrality and betweenness centrality, are commonly used to analyse the spatial networks formed by urban streets. This study considers straightness centrality, which refers to the extent to which a street acts as a direct and efficient route for movement between other streets in the network (Porta *et al.*, 2008). Regarding street selection, Urban Morphometrics (UMM) was used to identify streets with similar objective density metrics (Floor Areas Ratios/Plot Ratios) but exhibit different urban form characteristics. For instance, urban forms along the streets with similar population density can be further classified based on building heights, street widths, or architectural styles. The combination of MCA and UMM provided a structured and data-driven approach to identifying streets representing diverse urban characteristics crucial for studying perceived density. By leveraging these methods, it was ensured by field observations that the selected streets captured the desired variation.

Survey Design: The Multiple Sorting Task (MST)(Barnett, 2008; Canter, 1996) and Situation Judgement Task (SJT)(Wolcott *et al.*, 2020) were utilised as data collection methods in the form of two surveys for this study on perceived density. The initial survey (MST), conducted using Glasgow and Universal examples as cases, sought to uncover personal constructs and extract various factors within the urban environment that impact density perception, while the second survey (SJT) aimed to discern whether the perceived values of the urban environment were positive or negative. Both the methods used in this study are grounded in the theory of personal constructs by George A. Kelly (2017), which states that individuals interpret and understand the world through personal constructs (cognitive frameworks or mental categories to make sense of their experiences) (Kelly and Kelly, 2017). These constructs shape how individuals perceive and evaluate different aspects of their environment, including density, in the context of this study.

In the MST, participants are asked to sort or group images based on their perceived similarities. By engaging in this task, participants employ their constructs to categorise and organise the images according to their subjective criteria. Each participant may have unique personal constructs that guide their sorting process, reflecting their way of understanding and evaluating density. Similarly, the SJT presents participants with images perceived as high, moderate or low density by the individuals in the first survey to make qualitative judgements (positive /negative) related to density. These judgements are influenced by participants' constructs, which shape their perceptions and preferences regarding density. Their choices in the SJT reflect the individual interpretation and evaluation of density based on their constructs.

All data obtained was then content analysed (Kleinheksel *et al.*, 2020; Zhang and Wildemuth, 2009) and image analysis (Hook and Glaveanu, 2013). Content analysis allows for systematically interpreting textual responses from the multiple sorting and situation judgment tasks. It helps identify common themes, underlying patterns, and meanings in the participants' perception of density (Zhang and Wildemuth, 2009). Additionally, image analysis provides quantitative and qualitative insights into the visual elements of the urban environments presented to participants. Quantitative data, such as the percentage of green spaces or building heights, can objectively measure specific visual characteristics. Qualitative data, such as participants' comments on the visual appeal or sense of openness, offer a deeper understanding of their perceptions. Image analysis can be conducted using techniques such as object detection and segmentation (Debals and Brabandere, 2020) (applied in this research), visual feature extraction, eye tracking analysis, or even conventional image comparison methods, depending on the research objectives. These methods ensure that the findings are based on rigorous analysis and not influenced by the subjective biases of the researchers.

It must be noted that content analysis and image analysis do not directly provide statistical data. However, they generate qualitative data that can be processed and analysed using other methods, such as frequency analysis and magnitude estimation. Frequency analysis (Randall, 1987) is commonly used to analyse text data from content analysis. It assists in identifying patterns and recurring themes in the data and preferences related to density. In the context of density perception in urban environments, magnitude estimation (a psychophysical scaling technique that involves assigning numerical values to the perceived intensity of a stimulus without using a standard reference) can quantify participants' perceptions of specific visual components that contribute to their overall sense of density. Magnitude estimation provides a flexible and versatile approach for quantifying subjective perceptions and can be applied in various ways depending on the research objectives.

3.3. Application and Case Study

The framework for studying perceived density was applied and tested in the case study of Glasgow and Universal Illustrations over three steps. The study aimed to understand how people perceive density in environments featuring different objective densities.

The first phase involved the application of the framework in the case of Glasgow with two key steps. Firstly, streets were selected using Multiple Centrality Assessment (MCA) (Porta *et al.*, 2008), Urban Morphometrics (Fleischmann, 2019), and field observations. The objective was to identify streets with similar objective density but varying urban forms, ensuring a diverse representation of built environments across different areas of Glasgow, including the city centre and various districts. To ensure the identification of realistic factors and the study's accuracy, street perspectives were carefully chosen to capture the visual aspects of the urban environment from the sidewalks. This step allowed for a comprehensive examination of how different urban contexts influence people's perception of density. Secondly, the first survey, the Multiple Sorting Task (MST) (Barnett, 2008; Canter, 1996), was designed as an online web application. The MST involved sorting 27 images in triads based on perceived similarities. A diverse sample of participants, including laypeople, architectural students, and design and planning professionals, took part in the surveys, providing a range of perspectives on density perception. The survey was crucial in gathering subjective data and identifying the complex factors influencing how people perceive density in different urban settings.

The framework was also tested using 27 universal case examples of high-density streets. However, two exceptions were noted in this scenario. Firstly, the streets selected for the universal case were well-known examples of high-density areas identified by Density Atlas (MIT- DUSP, 2020), and they were not chosen based on the Multiple Centrality Assessment (MCA) and Urban Morphometrics methods like the streets in Glasgow. Secondly, the street perspectives used in the universal case were derived from Google Street imagery, which differed from the self-captured perspectives used in the Glasgow case. The hypothesis behind this approach was that the factors influencing the perception of density might differ between the Glasgow case (representing relative density) and the universal case examples (representing high density). Additionally, the difference in viewing angles might influence the perception of density due to the use of Google Street imagery in the universal case.

By comparing the results and findings from the Glasgow case and the universal case examples, the research aimed to gain insights into how the perception of density varies in different urban contexts. This comparison allowed us to understand whether the factors influencing density perception are consistent across different degrees of density and viewing angles or if they vary significantly based on the specific urban environment being studied. Content analysis of the raw data derived from MST identifies various factors contributing to the perception of high, moderate, and low density. In high-density areas, factors like tall buildings, narrow streets, high car and pedestrian density, and a compact urban form contribute to the perception of density and crowding. Moderate-density areas feature open spaces, dispersed urban forms, and a balanced mix of activities, providing a more neutral perception of density. In contrast, low-density areas have characteristics such as open spaces, front setbacks, low activity levels, and dispersed buildings, creating a sense of spaciousness and tranquillity. Both cases identified 63 factors classified into 17 categories, of which 20 critical factors (constructs) associated with high, moderate and low density are presented in Figure I.

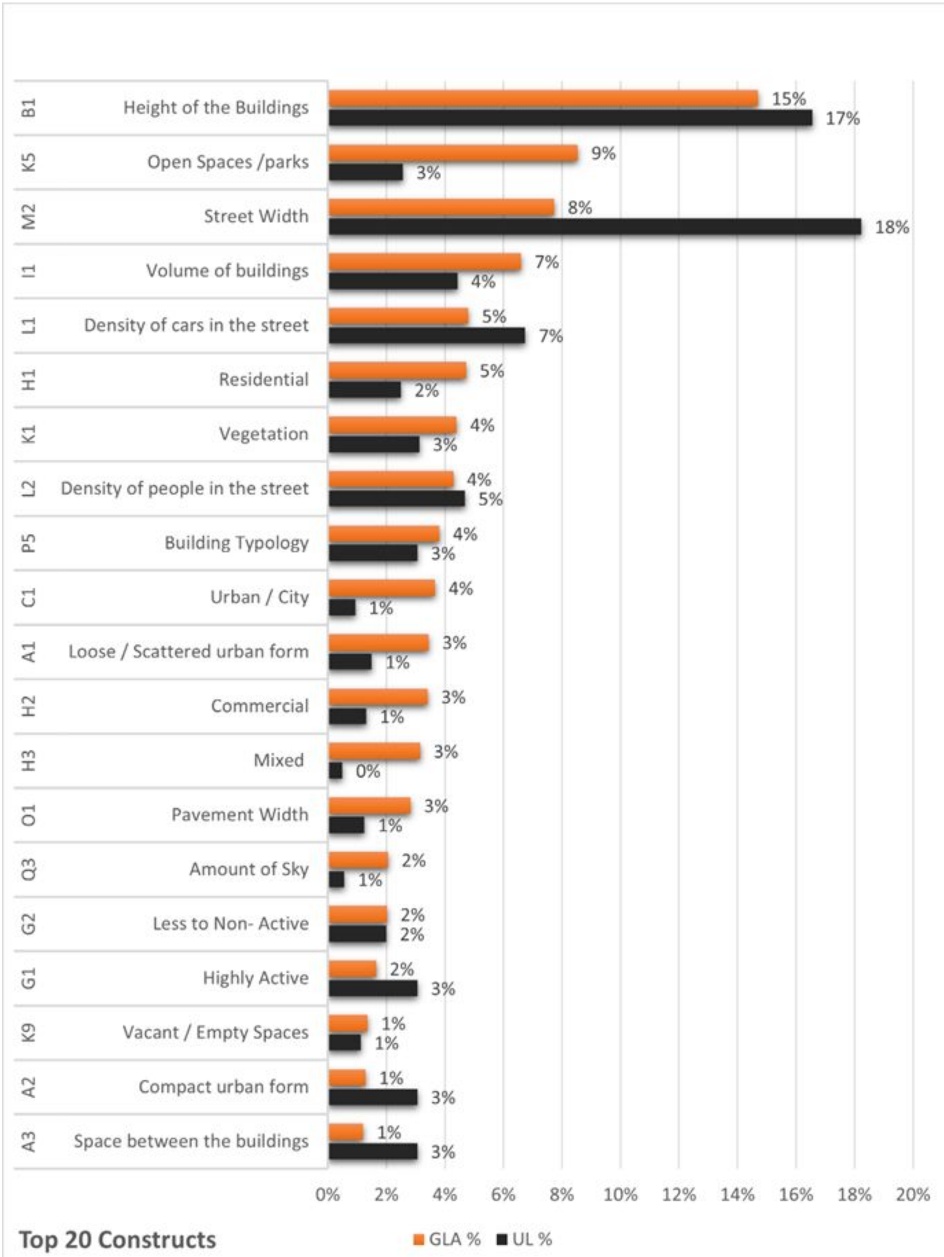

Figure 1. Phase 1- 20 Critical factors derived from MST

The Situation Judgment Task (SJT) survey was conducted in the second phase using Qualtrics. Participants were shown 16 images that included examples of images from both Glasgow and Universal illustrations perceived by people as high and moderate density from the first survey. It was conducted to complement the Multiple Sorting Task (MST) and provide qualitative evaluations of the perceived density in the presented images. While the MST helped identify a comprehensive list of 20 critical factors influencing the perception of density, it did not capture the specific reasons or explanations behind participants' evaluations. The SJT addressed this need by presenting participants with images perceived as high, moderate, or low density. They were asked to make qualitative judgments about density using three bipolar constructs: "Comfortable," "Cheerful," and "Vibrant" as positive attributes, and "Overwhelming," "Depressing," and "Dull" as negative attributes. Alongside these constructs, participants were provided with 13 factors, which they could choose as reasons for their positive or negative evaluations of density in each image. The results of this task are presented in Figure II.

Figure 2. Phase 2- Factors associated with a positive or negative perception of density – derived from SJT

The second phase identifies factors influencing positive and negative perceptions of urban environments. Positive perceptions include lively street activities, vegetation, diverse building uses, balanced building-to-sky ratio, people presence, and street width. Negative perceptions are associated with many cars, lack of people and activities, limited vegetation, and monotonous built form. Understanding these factors can help create attractive, vibrant, and inclusive urban. spaces, improving the overall well-being of residents.

During the third phase of the study, image analysis was conducted on all 54 images, including 27 images from Glasgow and 27 images from universal illustrations. This analysis aimed to identify visual components common to every urban environment and determine their visual composition. Understanding the contribution of each element was crucial in exploring how these components influence the perception of density. Each image was divided into segments using the image segmentation method, and the eight visual components were identified based on their distinct visual characteristics, as shown in Figure III. These components included buildings, streets, sky, vegetation, pavement, the density of people, cars, and streetscape elements.

By quantifying the representation of each visual component in the images, the study gained valuable insights into their contributions to the overall perception of density. This analysis provided a comprehensive understanding of how these components interact and influence people's perceptions of density in various urban environments. The findings from image analysis were then integrated with the results from the surveys and other research phases to establish upper and lower limits of eight components and develop a qualitative index for visual assessment of the urban environment, further enriching the comprehensive framework for studying perceived density.

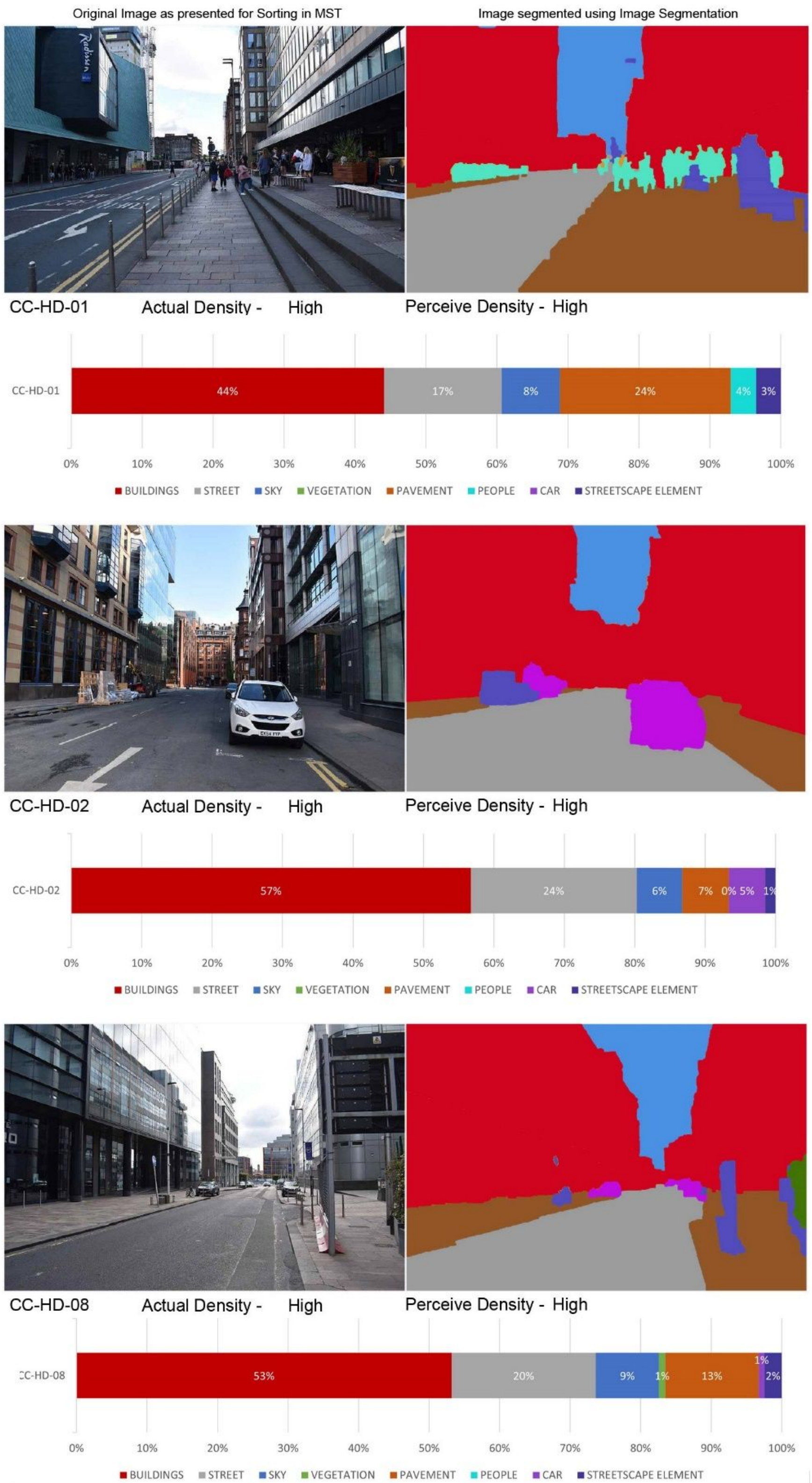

Figure 2. Phase 3- Image Segmentation

4. Discussion

The discussion of the findings underscores the significance of accounting for the highly subjective nature of density perception. The analysis of prior studies reveals the complex interplay of socio-cultural, personal, and environmental factors that shape how individuals perceive density in urban environments. This variability poses a substantial challenge for urban planners and designers seeking context-sensitive solutions. However, the proposed framework offers a systematic approach to address these complexities. By focusing on perceptual, symbolic, and temporal cues, this study provides a comprehensive tool for understanding and analysing density perception. This framework, rooted in Rapoport's approach, allows a more nuanced understanding of how people experience and interpret density in diverse urban settings.

While the limitations of prior studies, such as their reliance on subjective surveys and oversimplified stimuli, are evident, this study sets out to overcome these challenges. Moving forward, the study aims to employ a diverse and comprehensive study design. This will include larger sample sizes, varied stimuli, and real-time validation to enhance the reliability and applicability of our research. Doing so, makes it possible to further validate and refine the hypothesized system of cues and its quantitative thresholds. This will provide a more accurate understanding of density perception and contribute to developing user-responsive urban planning and design practices that consider the highly contextual and subjective nature of density perception. In this way, this study serves as a steppingstone toward more inclusive and effective approaches to shaping urban environments.

5. Conclusion

This paper proposed a systematic and user-responsive framework for density perception research to fill gaps. The framework captured density perception's subjectivity and urban form's impact on individual experiences. The Glasgow case study and universal examples show that the framework can comprehensively understand density perception across diverse urban environments. Although subjective biases and external factors can affect density interpretation, the study acknowledges these limitations.

As with any research, there are inherent constraints, such as the challenges of capturing the richness and complexity of human perception. This study identified three limitations. First, despite the comprehensive framework, density perception remains inherently subjective and influenced by individual preferences, cultural backgrounds, and experiences. The study cannot eliminate these subjective biases, which may impact the density interpretation. Second, the study primarily focused on the physical aspects of urban environments, such as building height and street width. However, it did not extensively consider external factors, such as weather conditions, lighting, or time of day, which can also influence density perception. Third, the study focused on cross-sectional data, providing insights into density perception at a specific moment. More longitudinal analysis to account for changes and variations in individual perceptions over time could reveal how density perception changes over time and with evolving urban developments. Additionally, future research can explore integrating advanced technologies, like virtual reality and immersive simulations, to enhance the framework's generalizability and reproducibility for deeper insights into density perception. Conducting cross-cultural studies in different regions can also provide a more comprehensive view of density perception worldwide.

Overall, this framework presented a significant step forward in comprehending the multifaceted nature of perceived density, and its application can pave the way for more informed urban planning and design decisions. The framework's practical applications extend to urban planning and design, promoting sustainable development, public health, and community engagement. By better understanding how people perceive density, cities can create more inclusive and liveable urban spaces that meet the needs and preferences of their residents, paving the way for a more sustainable and thriving urban future.

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