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Article

Spatial Cognition and Three-Dimensional Vertical Urban Design Guidelines—Cognitive Measurement and Modelling for Human Centre Design

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Abstract: Numerous studies have shown that the emotional wellbeing of urban populations is influenced by various aspects of urban development, such as social factors and the presence of walkable areas and green spaces. However, there is a lack of research that closely integrates urban design and cognition, particularly in the context of vertical and volumetric urbanism. This disconnect between design and science disciplines is evident when reviewing the limited research on emotional and spatial cognition in this specific urban context. This paper seeks to address that disconnect by proposing a comprehensive framework for the cognitive measurement and modelling of the built environment. This will involve exploring and measuring neural mechanisms, employing electroencephalogram (EEG) equipment to measure user responses in vertical and volumetric public spaces. The aim is to create a foundation for further studies in this field that is consistent and rigorous and can facilitate collaboration with cognitive neuroscientists by establishing a shared conceptual basis. The goal of this research is to develop a human-centric approach for urban design that is scientific and measurable, producing a set of urban design guidelines that incorporate cognitive measurement and modelling, with the broader intention to prioritize human needs and wellbeing within urban environments to make them more liveable.

Keywords: vertical urbanism; human centric design; spatial cognition; psychology

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1. Introduction

When we envision the concept of a "city", we often conjure an image dominated by tall buildings and a dense urban fabric. As our cities continue to stretch skywards, the high-rise is becoming the dominant building type and is often coupled with multiple levels of public realm designed to ease congestion at the ground level and link with adjacent developments. Hence, urban lives are evolving. In academic studies, most of the focus during this evolution has been placed on the technical aspects of tall buildings, such as maximizing the ratio of gross area and plot ratio for construction [1–3]. A number of theorists have also reflected on how this increased verticality can be achieved in an environmentally friendly way [4–6], and how the public spaces between buildings can be designed for liveability [7–9]. However, while decision makers and developers are generally interested in building more tall buildings to accommodate expanding urban populations, little attention has been given to studying the neural, cognitive consequences of living in them. The few studies that do exist on this topic are from the late 1990s and early 2000s [10–15], and only recently have scholars started to focus on vertical space in urban landscapes. Some scholars have criticised the focus on horizontal aspects in urban analysis and have called for more attention to be given to the "neglected verticality" of cities [16–18].

1.1. Sociological Perspective

The concept of 'vertical urbanism' emerged from a geopolitical standpoint that emphasised the territorial and military significance of these structures, as discussed by Elden (2012), Graham & Hewitt (2013), and Weizman (2002) [19–21]. More recently, Graham (2016) and Nethercote (2018) called for a shift towards a localised and people-centric approach to research on verticality. Whilst the research output related to the theme of 'vertical urbanism' encompasses diverse orientations, there is only a limited exploration of high-density and high-rise living from a more human and social perspective [22,23]. Harris (2015) argued for a thorough analysis of the vertical urban landscape by delving into ethnographic details, such as the way residents experience, embody, and inhabit the three-dimensional city [14]. Similarly, Nethercote (2018) explored the intricacies of urban developments, emphasizing the performative and constitutive nature of vertical expansion in shaping dynamic social relations [23]. Barrie et al. (2023) investigated the social value of community space in a vertical urban context using the particular case of a mixed-use, high-rise building, emphasizing the significance of social engagement and cultural landscape against the dominance of top-down political concerns in urban studies [24]. Going further, scientific and technological developments, including discoveries in brain physiology and cognitive psychology, the psychosocial determinants of health, and the spread of navigation and information technologies, have increased the pertinence of cognitive–environmental research on urban planning [25].

These scholars share a common focus on the social aspect of urban development, particularly the experiences of residents, users, and the evolving social dynamics in vertical urban spaces. They highlight the significant influence of physical environments on people's emotional states, encompassing both positive and negative aspects. Numerous studies have demonstrated that various urban elements, such as parks, gardens, rivers, and neighbourhood characteristics (including recreational resources, walkability, and green spaces), directly or indirectly impact the emotional wellbeing of urban populations. This influence is manifested through factors including physical activity, social interaction, and exposure to green spaces, all of which play a role in reducing stress, fostering positive emotions, and enabling relaxation for urban dwellers [26–31]. Exposure to the natural environment, in particular, is often associated with Kaplan's attention restoration theory, which suggests that being in nature alleviates the cognitive effort required for focused attention, leading to improved concentration and mental rejuvenation.

Within this context, the following key research questions can be raised: *How does the emotional response of people relate to physical and spatial building typologies? How do these spatial and physical characteristics shape their spatial cognition?*

This research aims to address these questions by establishing a scientific research methodology that applies cognitive measurement and modelling to urban forms and systems focused on the human experience. By doing so, the goal is to enhance the liveability and human-centeredness of spatial and social structures.

1.2. High-Density Living Environment with Its Emotional Responses

Recent research has shown that high-density buildings and infrastructures in large cities are more likely to have a negative impact on people's mood [32–35]. In this context, urban streets play a crucial role in influencing residents' emotions. [36–38]. The majority of studies examining the impact of streets on spatial cognition and emotions have primarily focused on the presence of vegetation. For example, research has shown that streets with a high concentration of trees and plants can help alleviate depressive symptoms and improve attention capacity [39,40]. Additionally, Jiang et al. (2020) found that an increase in tree canopies is associated with stress reduction, whereas understory vegetation has a negative impact on mental health [41]. These are consistent with the findings from Rapuano et al. (2022) and Shoval et al. (2018) that spaces shaped by variations in terrain elevations and types can evoke distinct emotions among diverse groups, as identified through experiments [42,43].

Furthermore, the findings from the emotional and spatial cognition study in the context of high-rise and high-density vertical urbanism are worth considering. It is notable that Sussman et al. (2020) highlighted how organised complexity in the urban environment tends to capture attention for longer durations. This is attributed to the heightened processing demands associated with complex visual scenes [44]. Additionally, this study suggests that volumetric urban forms, with their added density and spatial intricacy, may also impose greater processing demands on individuals.

In 1983, Ulrich introduced his 'psycho-evolutionary' theory, suggesting that people's preference for certain places is influenced by specific environmental characteristics such as complexity, focal points, ground surface texture, depth, and mystery [45]. Expanding on this, additional research indicates that while preference is a crucial factor, it represents just one of several emotions (including fear, interest, anger, and sadness) that significantly contribute to the psychological aspects of stress and restoration. For instance, a feeling of oppressiveness is primarily attributed to visual exposure to "artificial" elements or spaces such as tall buildings, artificial facades, and paved roads, which are usually inherently unfavourable and uncomfortable for humans [46]. When streetscapes provide a greater sense of safety, people often experience a heightened feeling of freedom and relaxation, which can alleviate the sense of oppressiveness and mental stress [47].

While research on emotional and spatial cognition in the context of vertical and volumetric urbanism is limited, the table below (Table 1) emphasises the important theories underlying the transformations and evolving concepts of urban cognition and the values of vertical urbanism. These theories are interconnected and supported by systematic and adaptive disciplines.

The urban environment plays a fundamental role in influencing various aspects of social activity, stratification, stress levels, synergistic activities, community engagement, and interactions. In particular, the built environment, including vertical and interior urban spaces, has a significant impact on urban cognition through factors such as sunlight, greenery, safety, noise, and the availability of diverse types and sizes of public spaces for recreation, relaxation, and gathering. It is important to note that the emotional and cognitive response to a place can influence people's choices at various levels, encompassing both physical and emotional aspects. This highlights the relevance of creating responsive places that cater to the needs of individuals, not just in a physical sense but also in an emotional sense.

Urban design and cognition are not always closely integrated in research, indicating a disconnect between the two fields. The field of urban design is typically associated with related design disciplines including architecture, landscape architecture, and urban planning, whilst cognition links with neuroscience, psychology, and human behaviour. There is a noticeable disconnect between these design and science disciplines. Urban designers may perceive morphology as a specialised activity focused on historical maps and obscure concepts such as 'morphogenetic' processes. On the other hand, studies of emotional and spatial cognition may overlook the impact of chance, contingency, and context when considering urban form. As a result, urban design and spatial cognition often appear to be heading in different directions or working at odds with each other.

Given this context, the concept of vertical urbanism, or living in high-rise dwellings, emphasizes a sociological and anthropological understanding of this urban phenomenon. The term 'vertical' introduces a unique research direction that diverges from the existing body of literature, which primarily focuses on studying people's lives along a horizontal axis. It seeks to investigate the vertical expansion of urban spaces, both upward and downward [20]. The notions of verticality, vertical urbanism, and volumetric urbanism encapsulate the idea of increased depth and height in urban environments. They encourage the exploration of new perspectives on everyday life in cities and shed light on the dimensions of segregation and division that come with this vertical way of living.

Table 1. Reviewing the changes and evolving terms of urban cognition and the value of vertical urbanism (Source: Authors).

Year	Author(s)	Methodology	Study Focus	Cognition Measures	Urban Form Measures
2017	Amandine Junot, Yvan Paquet, Charles Martin-Krumm [48]	This research employed a path analysis to assess the relationship between passion for outdoor activities, emotions, affiliation with nature, and environmental behaviours and collected data from 212 practitioners	Emotion, Behaviour	Harmonious passion related to positive emotions and obsessive passion related to negative emotions.	Outdoor environment and affiliation with nature
2017	I-Chun Tang, Yu-Ping Tsai, Ying-Ju Lin, Jyh-Horng Chen, Chao-Hsien Hsieh, Shih-Han Hung, William C. Sullivan, Hsing-Fen Tang, Chun-Yen Chang [49]	In the psychological study, the perceived restorative values of four types of landscape environments (urban, mountain, forest, and water) were evaluated by using questionnaires, and in the physiological study, brain activity was detected while viewing different types of landscape environments through fMRI.	Cognition, Environment	Investigating psychological responses to different types of landscape environments using the Perceived Restorative Scale (PRS): being away, fascination, extent (under which fall coherence and scope), and compatibility.	Urban and Natural landscapes, including mountains, forests, and water.
2018	Yuri Hadi, Tim Heath, Philip Oldfield [50]	Firstly, an evaluation on the architectural qualities of the space; secondly, observational analysis of how the spaces are used; thirdly, analysis of quantitative data on residents' access to the sky gardens; and finally interviews with the building owner, manager, architect, and residents themselves.	Cognition, Environment	Fear and anti-social behaviour pattern. Positive emotions to emerge in the sky gardens, providing sensations of peace and escapism.	Sky garden
2019	Michael Francis Norwooda, Ali Lakhania, Annick Maujeanb, Heidi Zeemana, Olivia Creuxa, Elizabeth Kendall [51]	This research uses various neuroimaging techniques, such as EEG (electroencephalography) and NIRS (near-infrared spectroscopy), to measure brain activity. Mood and emotion measures, such as self-report scales, are also used to assess subjective experiences.	Cognition, Environment	It examines the differences between natural and urban/non-natural environments in terms of brain responses and subjective experiences	Multiple
2019	Michael Francis Norwood, Ali Lakhania, Simone Fullagarf, Annick Maujean, Martin Downes, Jason Byrne, Anna Stewart, Bonnie Barber, Elizabeth Kendall [52]	Systematic review	Cognition, Environment	With the use of systematic review exploring the ability of the natural environment to promote behavioural, cognitive, or emotional change in young people	Road network (space syntax), natural environments

Table 1. *Cont.*

Year	Author(s)	Methodology	Study Focus	Cognition Measures	Urban Form Measures
2020	Alexander Coburn, Oshin Vartanian, Yoed N. Kenett, Marcos Nadal, Franziska Hartung, Gregor Hayn-Leichsenring, Gorka Navarrete, Jose L. Gonzalez-Mora e and Anjan Chatterjee [53]	Psychological experiment, fMRI. Correlation matrices are used to prepare the data for network analysis	Cognition, Environment, Indoor	To determine psychological dimensions that explain aesthetic responses to architectural scenes and their correlation with neural activation patterns. Three psychological components: fascination, explorability, and stimulation, which explain a significant portion of the variance in aesthetic response measures	Two architects independently rated every image on (a) perceived enclosure (open, closed), (b) ceiling height (high, low), and (c) contour (round, square).
2020	Otmar Bock [54]	Cognition was measured through participants' wayfinding performance in the grid-like mazes, both in virtual and imagined scenarios. The number of errors and time spent at interactions were both taken into account.	Cognition	Analysing the internal representation of surrounding space in human spatial cognition.Comparing wayfinding performance in horizontal and vertical orientations. Exploring the potential influence of asymmetrical permeability of buildings on the stacked representation of horizontal planes.	Multi-level buildings.
2021	Adam B. Weinberger, Alexander P. Christensen, Alexander Coburn, Anjan Chatterjee [55]	The experiment began with a brief slideshow during which participants were presented with each of their 16 randomly assigned images sequentially. This exposure was designed to familiarise participants with each image, as well as sensitise them to possible differences between the image types. Next, participants rated each image on 16 aesthetic criteria.	Cognition, Environment	Identifies three psychological dimensions (Fascination, Coherence, and Hominess) that contribute to aesthetic experiences induced by surrounding environment.	Analysing both built and natural environments. 16 aesthetic criteria: complexity, order, natural, beauty, personalness, interest, modernity, valence, stimulation, vitality, comfort, relaxation, hominess, uplift, approachability, and exportability
2021	Anjan Chatterjee, Alex Coburn, Adam Weinberger [56]	The authors conducted Psychometric Network Analysis (PNA) and Principal Components Analysis (PCA) on responses to curated images.	Cognition, Environment	Examining the role of natural features in architectural settings and identifying key psychological dimensions of aesthetic responses to architectural interiors. Identified three components: coherence, fascination, and hominess.	Interior space

Table 1. *Cont.*

Year	Author(s)	Methodology	Study Focus	Cognition Measures	Urban Form Measures
2022	Chongxian Chen, Haiwei Li, Weijing Luo, Jiehang Xie, Jing Yao, Longfeng Wu, Yu Xia [46]	Street view images of Guangzhou were captured, and street elements were extracted by pyramid scene parsing network. Data on six mood state indicators were collected via an online platform. A machine learning approach was proposed to predict the effects of street environment on mood in large urban areas in Guangzhou. A series of statistical analyses including stepwise regression, ridge regression, and lasso regression were conducted to assess the effects of street view elements on mood.	Cognition, Environment	Investigating the association between the street environment and mood at an urban scale. Six mood state indicators (motivated, happy, positive social emotion, focused, relaxed, and depressed)	Streets view elements (roads, vegetation, buildings, and the sky)
2022	Zakaria Djebbara, Ole B. Jensen, Francisco J. Parada, Klaus Gramann [57]	Review and case study	Cognition	The rate of change in sensory information in the visual system during motion. Designing spaces with a high rate of visual flow will make it appear as if one is speeding up because the high rate of environmental sensory information is associated with moving at higher speeds.	Built environment and environmental features
2022	Lan Luo, Bin Jiang [58]	Online photo-based experiment, questionnaire survey	Cognition, Environment	The study confirms the major role of perceived oppressiveness in interpreting the impact of urban streetscapes on mental stress in high-density cities.	The density of streetscape elements at eye level. Environmental exposure

1.3. Three-Dimensional Interior Public Space

The concept of vertical and volumetric public realms requires elements that establish a connection between buildings and their surroundings. These cues can either reinforce existing paths, landmarks, edges, and blocks or stand out from them. Additionally, vertical dependence, both at the ground level and in terms of elevator access, needs to be considered [59]. The integration of multi-level connections, akin to Alexander's analogy (1964), fundamentally transforms a hierarchical tree structure into a semi-lattice structure. This introduces diverse and permeable urban experiences [60]. Archigram, for instance, highlighted the use of bi-layered connections, such as subways in New York City, to illustrate the limited adoption of multi-level connections and the importance of considering diagonal connections [61]. It is worth noting that most cities have, at most, a tri-layered connection system comprising below ground, at ground level, and above ground elements, all of which remain relatively close to the ground in comparison to the height of buildings.

In order to validate these characteristics, this research sought to establish a connection between the built environment and its influence on mental and physical wellbeing, as well as social relationships. This connection was identified as being crucial for the successful execution of different intended uses. In essence, the diverse range of spatial conditions and environments has an impact on the choices individuals can make, operating at various levels. This necessitates strategic experimentation that encompasses both horizontal and vertical dimensions:

- It affects where people can go, and where they cannot, both physical and visible in the conditions of permeability, accessibility, and walkability, which have an impact on physical and mental health.
- It affects the range of uses available to people, which can have a negative effect on social stratification, segregation, crime, and fear of crime.
- It affects the degree to which people can use a given place for different purposes, which has an impact on place identity and a sense of belonging.
- It affects people's choice of sensory experiences, which impacts physical and mental health with different conditions such as sunlight, greenery, safety, and gathering.
- It affects the extent to which people can make different choices regarding movement, usage, amenities, and visible experiences, which have an impact on community engagement and interaction, relaxation, joy, stress levels, and synergistic activities.
- It affects the degree to which people feel they are being protected from harm within a given place, which impacts physical and mental health, conditions of safety, security, fear of crime, and social stratification.

In order to recognise how unique spatial conditions and environmental factors can contribute to the development of distinct characteristics and responsive environments, it is crucial to explore spatial cognitive correlation to gain a comprehensive understanding and anticipate user behaviour patterns, particularly their emotional responses, in relation to the spatial layout and various morphological conditions present. This research provides both a cognitive analysis and morphological analysis of the existing urban form or fabric.

2. Research Methodology

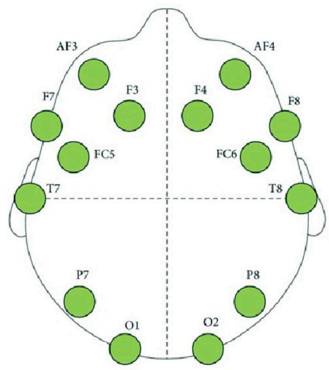
The research of Huang et al. (2020) and Herranz-Pascual et al. (2019) both demonstrated the importance of integrating urban design and research with scientific methods to accurately measure human emotions, preferences, and responses within our built environment [62,63]. This integration can potentially lead to the development of improved urban spaces and provide a more comprehensive understanding of the operational aspects of urban design, including the arrangement and composition of structures and spatial organisation.

To achieve this, this research utilised EEG equipment to measure (see Figure 1) and predict user responses and emotions in vertical and volumetric public spaces with varying levels of density. Excess Post-Exercise Oxygen Consumption (EPOC) equipment was employed; POC is the amount of oxygen required to restore your body to its normal, resting level of metabolic function. By conducting this approach, a deeper understanding of how individuals perceive and engage with different types of public areas can be gained. EEG and Electromyography (EMG) are techniques used to measure brain activity by monitoring changes in cerebral blood oxygenation. Cognitive neuroscientists have been utilizing these methods since the early 1990s to investigate the neurological underpinnings of cognition [64]. However, applying EEG and EMG to the study of urban design presents challenges. Cash et al. (2022) highlight the need for specialised approaches in design research, as EEG and EMG require strict experimental control and entail constraints that may conflict with the inherent characteristics of design [65]. Currently, there is limited guidance available on how to effectively utilize EEG and EMG as research methods in the field of design. While there is ample literature on the methodology of EEG in neuroscience, it tends to be highly technical and not easily accessible for design researchers [66].

To conduct the research systematically, the researchers utilised virtual reality (VR) goggles to analyse '3D urban interior spaces'. These spaces were presented on a screen and incorporated various key variables such as sunlight levels, the presence or absence of greenery, and the complexity of multi-layered interior public realms and open spaces. The goal was to assess participants' perception and emotional connection to these stimuli. In the tests, electrical activity in the brain was measured using an EEG machine, which involved attaching small electrodes to the scalp to monitor brain activity.

There are no age, gender, or occupation restrictions for participants in this procedure, and all safety regulations have been followed to ensure there is no risk involved. In order to guarantee safety throughout the entire process, participants underwent a screening. The test itself required around 10 min of preparation and 20 min of actual testing. Brain wave activity was analysed from EEG data, which were collected while participants experienced different stimuli related to six different emotions. These EEG data use a series of parameters of building typology to evaluate and examine how users perceive and comprehend emotions and spatial aspects within the context of vertical and volumetric building types.

Band	Frequency range (Hz)	Association
Delta	0.5–4	Deep sleep
Theta	4–8	Consciousness slips Drowsiness Unconscious material Creative inspiration Deep meditation
Alpha	8–13	Relaxed awareness Eye closing
Beta	14–30	Active thinking, Attention Motor behavior Focusing on the outside world Solving concrete problems
Gamma	30+	Sensory processing Certain cognitive motor function



Emotiv EPOC electrodes aligned with positions in the 10–20 system.

Figure 1. Emotiv EPOC electrodes and its band, frequency range. (Source: Authors).

3. Case Study for the 3D Simulation of Vertical Urban Settings

A case study in Singapore focused on the micro-scale of vertical and volumetric built environments, specifically using a landmark building typology that reaches a height of 280 m and incorporates mixed-use programs. Singapore serves as a representative example of vertical and volumetric interior urban space for measuring spatial cognition, with the building CapitaSpring being selected for particular focus at the micro-scale due to the way it utilises multi-layered interior public space.

The objective of this research was to model and test a unique series of spaces within the interior public realm. To achieve this, a model of the selected site was simulated, and a set of nine parameters of variation were devised and tested based on the key components of urban space, applying a range of changes to the environments (Table 2).

Table 2. Nine parameters of variation and their indicators (Source: Authors).

Nine Parameters for Urban Design Measurement Tools
Greenery
1. Select a scene at each level and incorporate a diverse range of greenery, following the specified percentages.
2. Generate each view, varying the specified percentages between 20% and 80%.
3. Compile images for the simulation video.
Accessibility
1. Select a scene at each level and illustrate access via elevator, escalators, and staircases, modelled to represent specified percentages ranging from 20% to 80%.
2. Render each view to showcase various degrees of accessibility.
3. Compile images for the simulation video.
Walkability
Set a wider view angle at a specific space on each level to showcase different walkability scenarios.
1. Reflect high walkability with open, empty interior spaces.
2. Include office functions to simulate 20% occupancy and its effect on walkability.
3. Increase occupancy to 40% to demonstrate the impact on walkable areas.
4. Showcase a fully occupied floor area at 80%, where only walkable space around the lift lobby is accessible.
Permeability
Set a broader view angle for one space at each level.
1. Arrange retail facilities on both sides of the corridor with a narrow space for circulation in between (20%).
2. Position retail facilities on both sides of the corridor with a wider walkway in between to facilitate smoother circulation (40%).
3. Incorporate retail facilities on both sides of the corridor and create a wider central void, allowing for sightlines, atrium views, and escalator views.
4. Introduce a larger opening and wider atrium view to enhance the overall permeability and open spatial experience.
Diversity
Diversity refers to the abundance of experiences within interior spaces.
1. Demonstrate distinct functions tailored for different age groups, such as spaces for children, adults, and the elderly.
2. Highlight a wide range of amenities, including exhibitions, play areas, skateboarding zones, art displays, and more.
Economic Catchment
Economic catchment areas comprise locations that drive consumption and spending. These areas encompass various establishments, such as restaurants, shops, event spaces, clinics, gyms, kids' play areas, and more.
Safety
Rooftop analysis
1. Floor material
2. Handrail
Light
1. Illuminate each level differently to capture the changing ambiance from morning until night.
2. Render the same view 4 times, each with different light settings to emphasise varying moods and effects.
3. Compile the rendered images to create a comprehensive lighting variation simulation.
Cultural Identity/Aesthetics
Incorporate elements that reflect the local culture of the place, such as those evoking Singapore's distinctive cultural traits that resonate with people. Ensure these cultural representations are thoughtfully integrated across multiple levels.

CapitaSpring in Singapore stands at a height of 280 m, spanning across 51 stories, and covering a total area of 93,000 square meters. This multifunctional building (Figure 2) includes a hotel, office, and retail spaces, with this research focusing on conducting experiments to understand the emotional and spatial perception of users within these specific spatial settings and environments.

This research involved creating a three-dimensional simulation that focused on three distinct floors with public access and transitional areas. These floors include the Atrium, which serves as both a public and commercial space, the Middle level which comprises residential and office areas, and the Sky Garden, a private space accessible to the community. The aim was to assess emotional responses based on nine key parameters for urban design and four spatial characteristics (Figure 3).

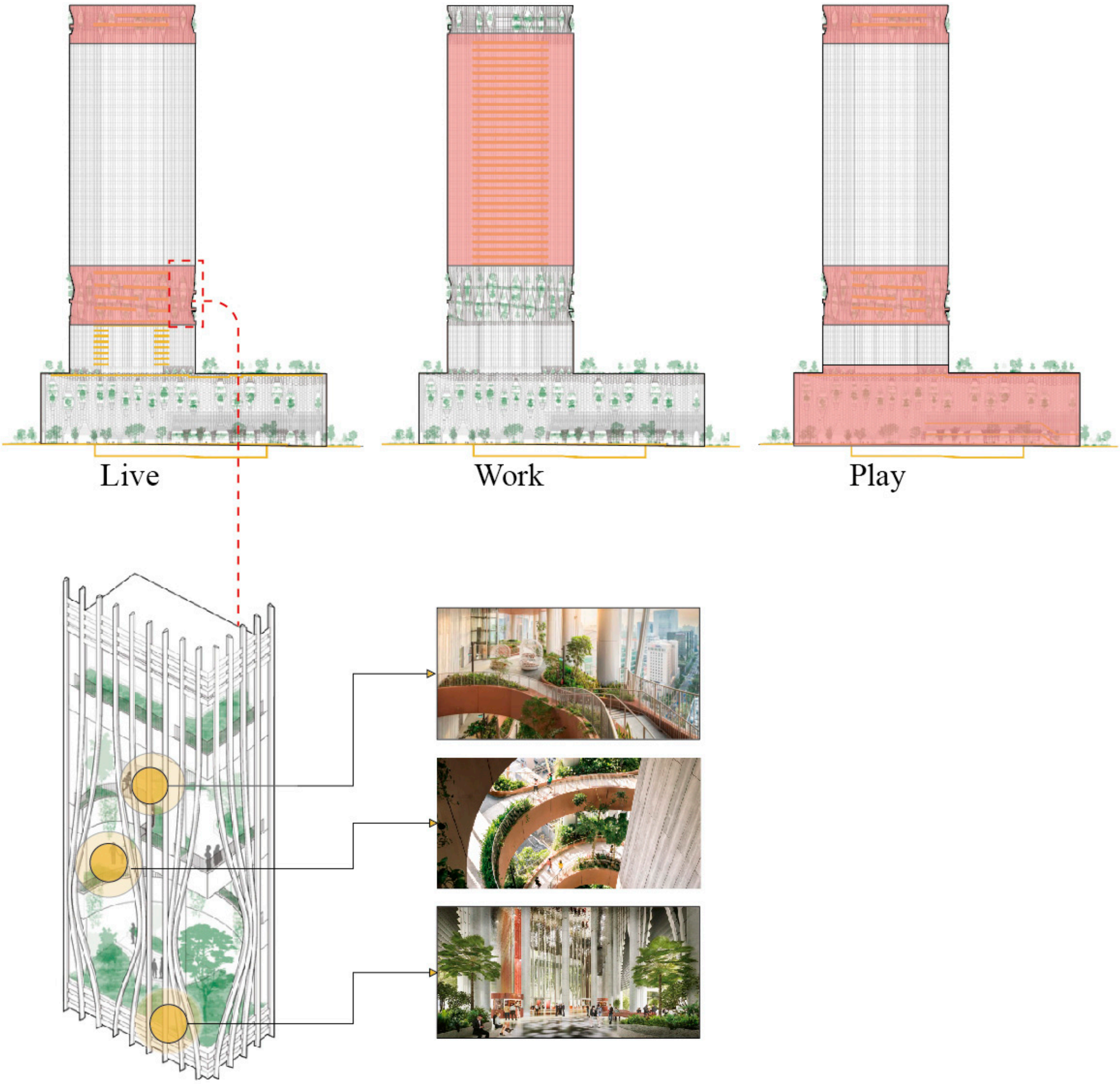


Figure 2. CapitaSpring in Singapore (Source: Authors).

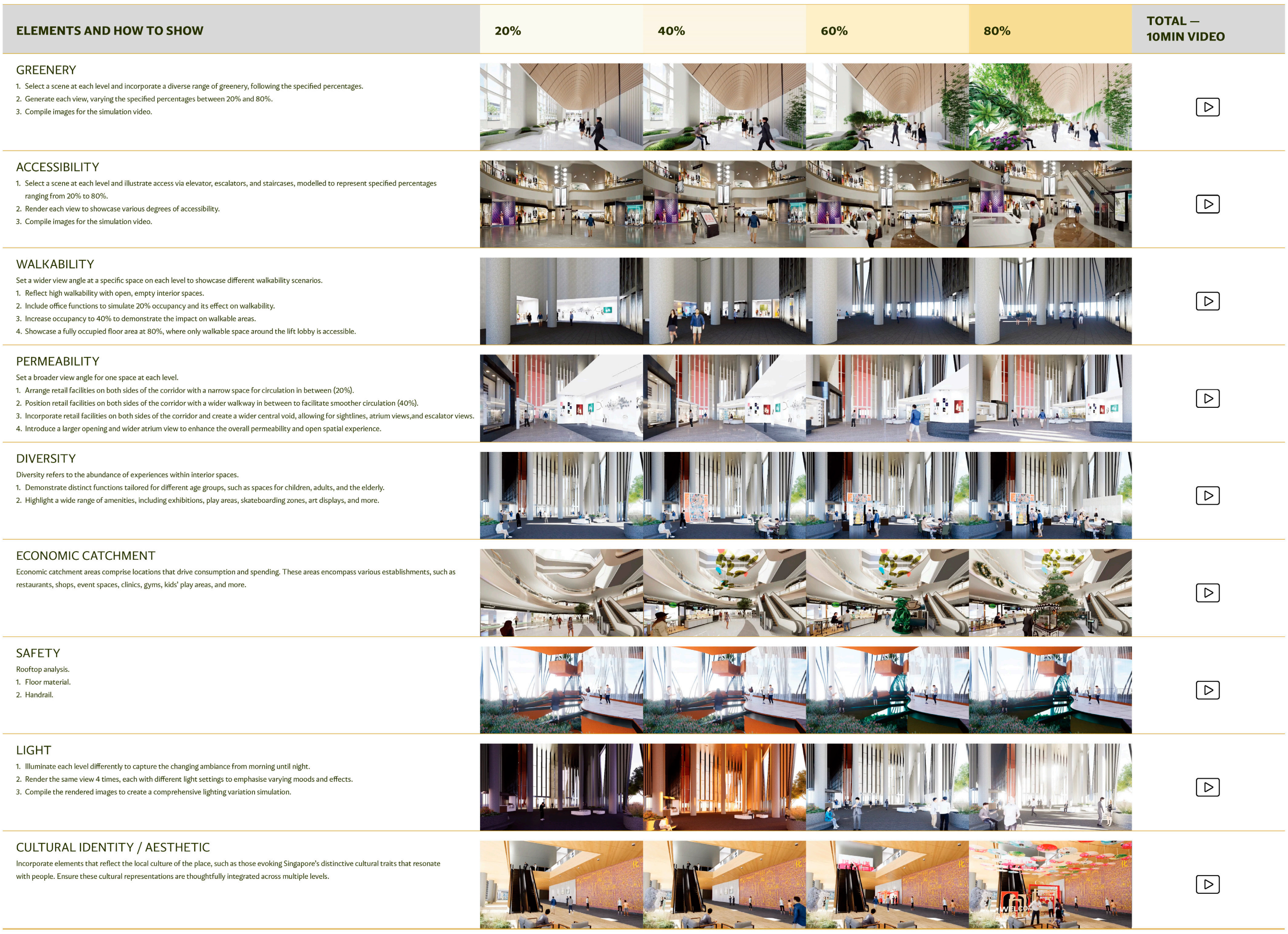


Figure 3. Simulations, scaling process for modelling using parameters from urban design framework to test users' emotions using EEG using CapitaSpring in Singapore (Source: Authors).

4. Data Collection for Emotional Spatial Cognition

The research selected a total of 40 participants from different cultural backgrounds and age groups, ranging from 16 to 75 years old, including both residents and visitors to Hong Kong. The data analysis processes included an AI tools and algorithms that was designed to avoid bias in the findings. The reasoning for the selection of Hong Kong as a case study was two-fold; the city is a useful example of highly dense, highly vertical urbanism and it is the base of the university and research lab for the research team. The data collection was conducted in the School of Design, Urban Lab in Hong Kong Polytechnic University from January 2023 to July 2023. An initial pilot study of 10 participants was following by a larger study of 30 participants. EEG data were analysed using AI generators and Google Vision AI to discover a 'correlation index' for emotional responses to spatial conditions.

The EEG testing procedure was as follows:

This study was carried out by a trained EEG technician within the research team and took approximately 10 min for preparation and 20 min for testing.

1. The participants were asked to relax in a reclining chair or lie on a bed.
2. A total of 16 electrodes were attached to the participants' scalp with a special paste.
3. The participants were asked to relax and be still.
4. Once the recording began, the participants were requested to remain still throughout the test. The participants were monitored to observe any movements that can cause an inaccurate reading, such as swallowing or blinking. The recording could be stopped periodically to let the participant rest or reposition him/herself.

5. Analysis

For EEG data collection, the following classification process was followed (Figure 4):

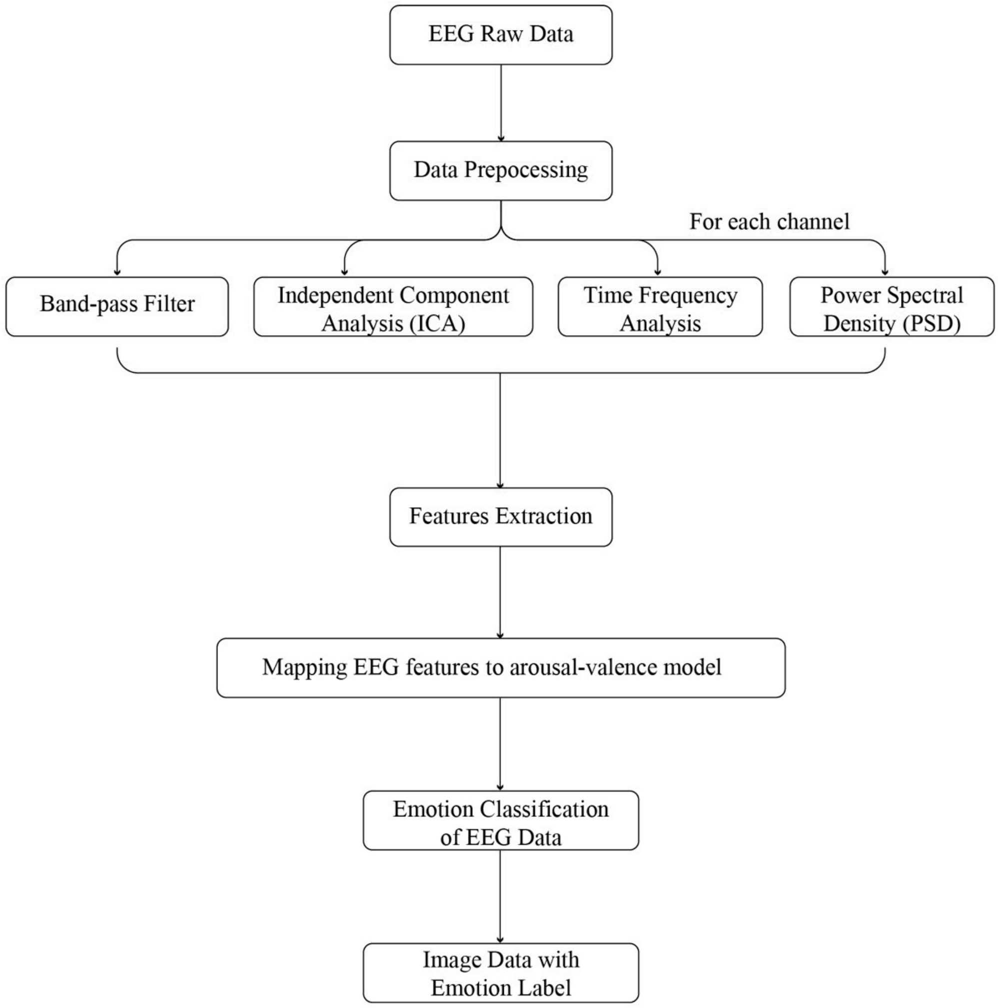


Figure 4. Dataset classification (Source: Authors).

The analysis commenced with data preprocessing in matrix laboratory (MATLAB), employing a range of algorithms designed for both simple and advanced electrophysiological data analysis. The initial step in data preprocessing involved the application of a band-pass filter, filtering the raw data within a frequency range of 1 Hz to 50 Hz. This spectral domain covers five significant EEG frequency bands: Delta (0–4 Hz), Theta (4–7 Hz), Alpha (7–13 Hz), Beta (13–30 Hz), and Gamma (30–50 Hz). Subsequently, Independent Component Analysis (ICA) was applied to effectively remove artifacts such as eye blinks and muscle activity.

To extract features from the EEG data recorded from each channel, time-frequency analysis was performed, enabling the examination of spectral content variations over time, which was assessed over a duration of 10 min and 10 s in this study. Additionally, Power Spectral Density (PSD) was employed to analyse the power distribution of EEG signals within each frequency band.

Observing how these spectral patterns evolve over time, in response to specific stimuli presented in the test material (in this case, a simulation video of CapitaSpring), in conjunction with insights from prior studies on EEG patterns associated with arousal–valence levels, facilitated the classification of the EEG data into six distinct emotions [67,68].

Lastly, an image dataset, labelled with emotional categories, was generated based on timestamp information in the EEG data. These image data, containing additional information regarding the floor and variations in relevant parameters, will serve as a valuable resource for further findings.

5.1. Arousal–Valence Model and Six Emotions Classification

In our study, the well-established arousal–valence model originally proposed by Russell in 1979 [69] was employed. This two-dimensional model of emotion is commonly utilised for categorizing emotions. Building upon this, we applied a modified version of Russell's model (Figure 5), introducing three positive emotions, 'Amazement', 'Joy', and 'Amusement', and three negative emotions 'Unpleasantness', 'Frustration', and 'Gloom'. This adapted model served as the framework for our emotional classification.

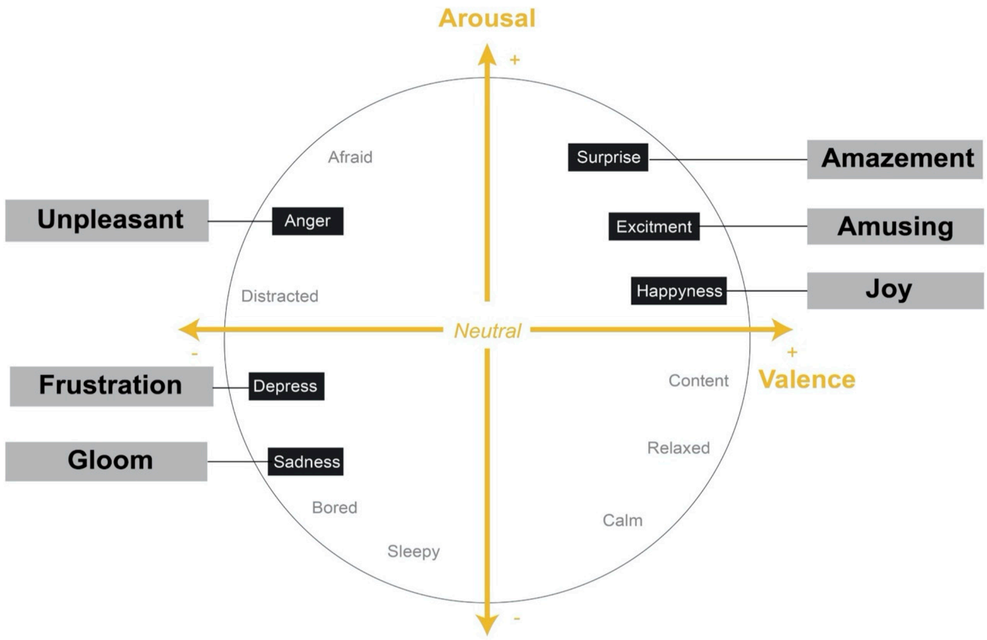


Figure 5. Arousal–valence model in our study (Source: Authors).

5.2. Mapping EEG Features to Emotion Modelling

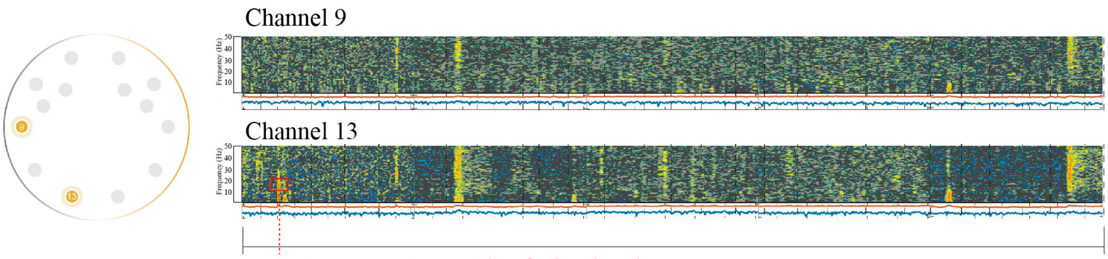
Researchers have long sought to establish the relationship between EEG patterns and arousal–valence levels. A study by Reuderink et al. in 2013 demonstrated a noteworthy connection regarding valence–arousal parameters [70]. Their findings indicated a significant reduction in theta activity in the frontal lobe for states characterised by high valence. Other research has shed light on the role of different brain regions in emotional elicitation. The frontal lobe has been implicated in the generation of surprise, while happiness and disgust have been associated with the temporal and occipital lobes, respectively. Additionally, sadness has been linked to activity in the parietal lobe [71]. The emotion classification was accomplished by examining features extracted through time-frequency analysis and Power Spectral Density (PSD) analysis based on the findings and insights in these existing studies.

5.3. Image Data with Emotion Label

To investigate the correlation between spatial elements and the six distinct emotions, we established image data subsequent to the classification of emotions. These image data enabled us to precisely associate emotional states with various spatial elements within the video, including parameters and floor information. This dataset was constructed by leveraging the emotion-labelled EEG data, which contained timestamp information representing the specific time points during the simulation video.

These timestamps were extracted from the EEG data to create six individual timetables, each corresponding to one of the six emotions. These timetables accurately documented the exact moments when participants experienced emotional arousal during the EEG test. The image data were curated by capturing specific scenes from the video that corresponded to these emotional states using these timetables. Ten Participants' EEG data analysis for CapitaSpring are following (Figures 6–9):

Example of Features Extraction of Classification for Joy & Amusing



Timestamp 00:00 01:20–01:25 (example of stimulated moment) 10:10

Data No.	Timestamp	Location	Parameter	Variation
Participant 5	01:20–01:25	Atrium	Walkability	20%
Participant 3	04:35–04:40	Atrium	Permeability	80%
Participant 3	09:00–09:05	Atrium	Culture	40%
Participant 7	09:15–09:25	Medium Level	Culture	40 60%

Location: Atrium
Walkability 20%

Location: Atrium
Permeability 80%

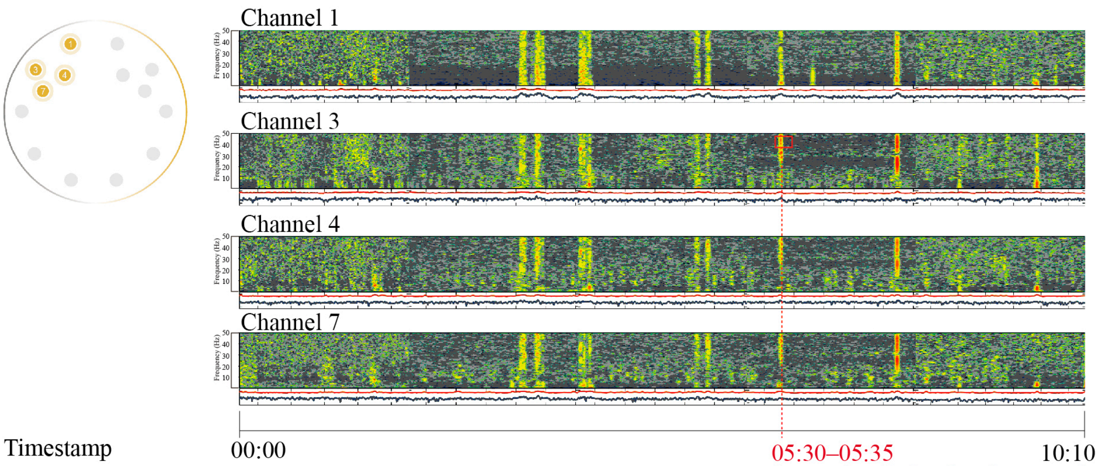
Location: Atrium
Culture 40%

Location: Medium Level
Culture 40–60%

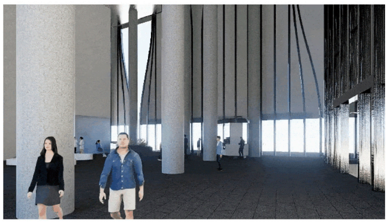
* Detail informations of the scenes are in the table above

Figure 6. Joy and amusement EEG analysis (Source: Authors).

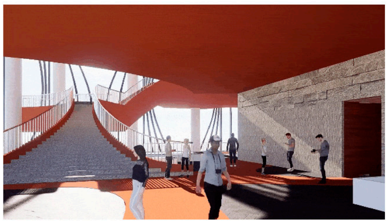
Example of Features Extraction of Classification for Amazement



Data No.	Timestamp	Location	Parameter	Variation
Participant 1	01:20–01:30	Atrium	Walkability	60–80%
Participant 1	02:20–02:25	Sky Garden	Walkability	80%
Participant 3	02:25–02:55	Sky Garden	Vertical	No Variation
Participant 3	04:05–04:15	Sky Garden	Greenery	40–60%
Participant 3	05:15–05:20	Sky Garden	Permeability	80%
Participant 2	05:20–05:25	Atrium	Diversity	20%
Participant 7	05:30–05:35	Atrium	Diversity	60%
Participant 3	05:50–05:55	Medium Level	Diversity	60%
Participant 2	06:40–06:45	Atrium	Economic Catchment	40%
Participant 5	07:20–07:30	Sky Garden	Economic Catchment	20–40%
Participant 3	06:40–06:45	Atrium	Lighting	80%
Participant 3	08:10–08:20	Medium Level	Lighting	40–60%
Participant 7	09:15–09:20	Medium Level	Culture	40%



Location: Atrium
Walkability 60–80%

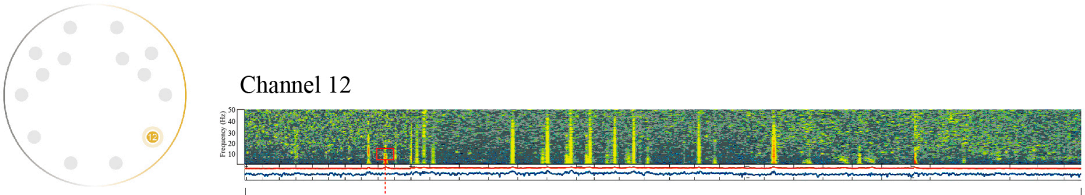


Location: Sky Garden
Walkability 80%

* Detail informations of the scenes are red highlighted in the table above

Figure 7. Amazement (surprise) EEG analysis at atrium and sky garden with different walkability conditions (Source: Authors).

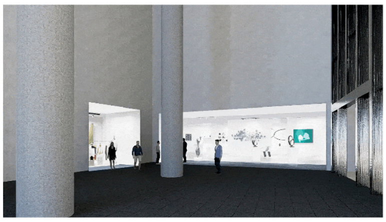
Example of Features Extraction of Classification for Gloom



Timestamp 00:00 01:10–01:15 (example of stimulated moment) 10:10

Data No.	Timestamp	Location	Parameter	Variation
Participant 1	00:00–01:05	Sky Garden	Accessibility	60%
Participant 5	01:10–01:15	Atrium	Walkability	20%
Participant 2	02:00–02:05	Medium Level	Walkability	80%
Participant 6	03:25–03:30	Medium Level	Greenery	20%
Participant 2	06:35–06:40	Atrium	Economic Catchment	20%
Participant 3	07:35–07:40	Atrium	Lighting	20%
Participant 6	08:05–08:10	Sky Garden	Lighting	20%

Location: Sky Garden
Accessibility 60%

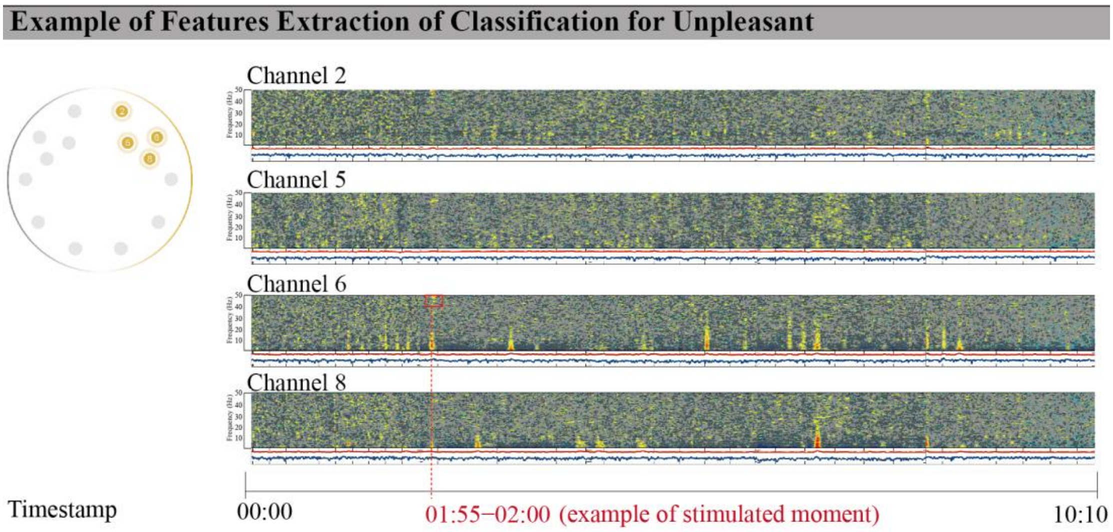


Location: Atrium
Walkability 20%

Location: Middle Level
Walkability 80%

* Detail informations of the scenes are red highlighted in the table above

Figure 8. Feeling of gloom—EEG analysis at atrium, medium level, and sky garden using different accessibility and walkability conditions (Source: Authors).



Data No.	Timestamp	Location	Parameter	Variation
Participant 2	00:20–00:25	Atrium	Accessibility	60%
Participant 7	00:40–00:50	Medium Level	Accessibility	60–80%
Participant 7	01:55–02:00	Medium Level	Walkability	60%
Participant 3	03:55–04:00	Medium Level	Greenery	80%
Participant 5	05:25–05:30	Atrium	Diversity	20%
Participant 1	07:30–07:35	Sky Garden	Economic Catchment	80%
Participant 4	09:05–09:10	Atrium	Culture	80%
Participant 4	09:25–09:35	Medium Level	Culture	60–80%

* Detail informations of the scenes are red highlighted in the table above

Figure 9. Unpleasant feeling—EEG analysis at atrium, medium level using different variations in accessibility (Source: Authors).

6. Findings

The comprehensive analysis of the EEG data encompassed six distinct emotional responses, revealing positive emotions as detailed in Tables 3 and 4, and negative emotions documented in Tables 5–7.

- Joy and amusement

Table 3. Joy and amusement emotional responses (Source: Authors).

Joy and Amusement		
Level	**Parameter**	**Variation**
Atrium	Walkability	60–80%
Middle Level	Permeability	Above 80%

- Amazement and surprise

Table 4. Amazement and surprise emotional responses (Source: Authors).

Amazement and Surprise		
Level	**Parameter**	**Variation**
Atrium	Walkability	60–80%
	Diversity	below 20%
		60–80%
	Economic catchment	40–60%
Middle Level	Lighting	80% above
	Diversity	60–80%
	Lighting	40–60%
	Culture	40–60%
Sky Garden	Vertical accessibility	80% above
	Greenery	40–60%
	Permeability	above 80%
	Economic catchment	20–40%

- Feeling of gloom

Table 5. The feeling of gloom responses by participants (Source: Authors).

Gloom		
Level	**Parameter**	**Variation**
Atrium	Walkability	below 20%
	Greenery	below 20%
	Lighting	below 20%
	Economic catchment	below 20%
Middle Level	Walkability	80% above
Sky Garden	Accessibility	60–80%
	Lighting	20% below

- Feeling of frustration

Table 6. The feeling of frustration responses by participants (Source: Authors).

Frustration		
Level	**Parameter**	**Variation**
Atrium	Walkability	20% below
Sky Garden	Culture	40–60%

- Unpleasant feeling

Table 7. The feeling of unpleasant responses by participants (Source: Authors, 2023).

Unpleasant		
Level	**Parameter**	**Variation**
Atrium	Accessibility	60–80%
	Diversity	20% below
	Culture	60–80%
Medium Level	Accessibility	60–80%
	Walkability	60–80%
	Greenery	80% above
	Culture	60–80%
Sky Garden	Economic catchment	80% above

To summarise, the analysis of the EEG data revealed several positive emotions, including 20 instances of amazement, 3 instances of amusement, and 3 instances of joyfulness. Negative emotions were also identified, with 12 responses indicating an unpleasant feeling, 8 instances of gloom, and 2 instances of frustration (Figure 10). These negative emotions were associated with factors such as the high density of economic catchment, restricted visual permeability and legibility, and the experience of travelling through interior public spaces and realms with low light levels. However, some respondents out of the 40 participants have mixed feelings, such as amazement together with joyfulness, thus, overall, we have 46 types of emotional response.

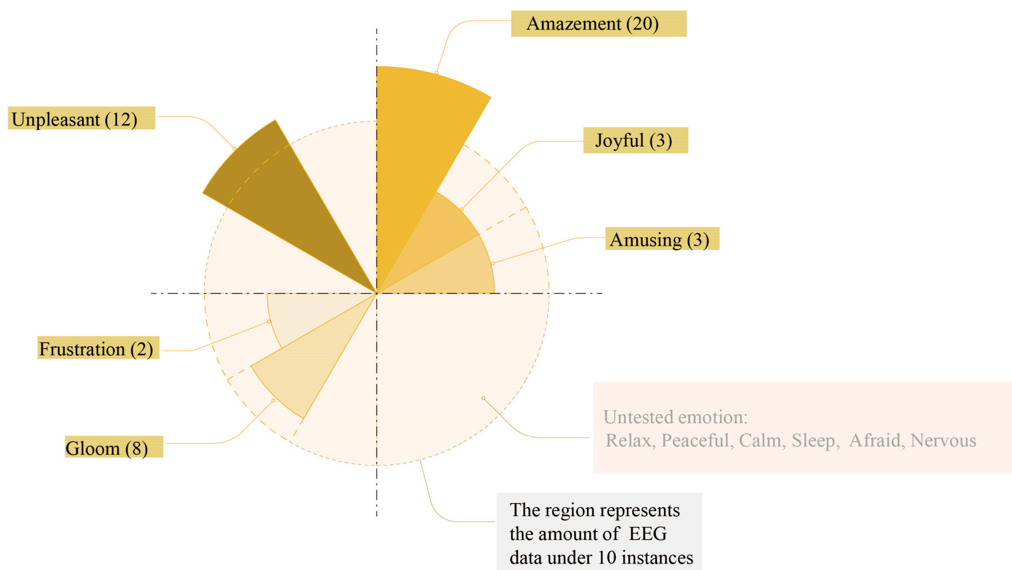


Figure 10. Findings for EEG data analysis (Source: Authors). The light red dashed circles represent the number of instances is less than ten, and the quantity of instances for each emotion is indicated next to different coloured sectors.

In detail, for the 'amazement and surprise' response at the atrium (ground level) in relation to:

1. The factors that contributed to creating a sense of amazement among people included a walkability range of 60% to 80%, well-defined boundaries of spaces, zoning areas with bustling activities, and a comfortable depth of space with high ceilings, especially with a visibility of the sky above 3.3%. Additionally, having less than 36% wall coverage, fewer than 35% column numbers, a user density below 0.1%, and stable, comfortable flooring with a satisfaction level above 24.5% were all elements that contributed to this feeling of amazement.

2. Regarding the aspect of 'Diversity', when the variation in the boundary and scale of the space is kept below 20% alongside moderate depth, a high ceiling, 5% visibility of the sky, less than 55% of walls with permeability, over 1.5% greenery and trees, and less than 10% of walls with visible accessibility, the users experience a sense of amazement. Interestingly, when the variation in 'Diversity' ranges from 60% to 80%, it also elicits a feeling of amazement among users. This response is further enhanced by maintaining less than 38% walls for visibility, a minimum of 2% chairs and seating areas, less than 6.1% user density, less than 1.1% column numbers within the spaces, and over 1.7% art paintings and decorations.
3. On the ground level, the feeling of amazement is enhanced by various factors. These include an economic catchment with a variation ranging from 40% to 60% and a variable depth of space with high ceilings, particularly allowing a maximum of 68% visibility through the walls. Additionally, a minimal presence of solid doors (less than 0.8%), a significant amount of greenery and trees (over 0.5%), a user density of no more than 5.4%, a minimum of 2.5% columns within the space, and a shopping counter occupancy of less than 5.5% all contribute to creating a sense of amazement in the atrium area.
4. A feeling of amazement can be achieved by implementing specific parameters that contribute to the overall environment. These parameters include setting the lighting at a variation above 80%, incorporating variable depth of space with high ceilings, ensuring maximum 60% wall accessibility, incorporating more than 0.6% of trees and greenery, maintaining a minimum density of 9.6% for uses, and providing 13.5% of accessible flooring area. These factors collectively contribute to creating a sense of amazement.

At the mid-floor levels (living and working spaces), the following emotional responses were found:

1. Diversity with 60% to 80% variation, moderate busy space with wide and long depth, less than 38% of walls, minimum 2% of seating areas within the space, 19% of ceiling coverage, more than 4.4% of the visible skyline, less than 6.1% of people, and minimum 21% of safe accessible flooring area and colour create amazement at the mid-floor level of public space.
2. With the parameter of lighting between 40% and 60% of variation, moderate depth with wide space, especially less than 38% of walls within the accessible space, 19% ceiling coverage, minimum 1.2% seating area, less than 6.1% users' density, and less than 1.1% column numbers within the space enhance amazement.
3. With the parameter of cultural aesthetic between 40% and 60% of variation, moderate depth with wide space, particularly, less than 36% of walls for visible accessibility, 27% of ceiling coverage, minimum 1.2% seating area, less than 7.6% users' density, and 10% of art pieces and decoration create amazement at interior public spaces and realm at the medium level of working and living vertical spaces.

Within the three levels of the upper sky garden (privately owned public space), the following emotional responses were found:

1. Walkability at above 80%, moderate busy space with wide and long depth, especially, less than 20% of walls, 31% of ceiling coverage, more than 4.4% of the visible skyline, less than 3.8% of people, and minimum 22.5% of flooring levels changes and colour create a feeling of amazement at the sky garden, the top floor level of public space.
2. Greenery between 40% and 60% variation, narrow but level changes in space with depth, especially more than 5% of visible sky, less than 15% of walls for the visible linkage and accessibility, more than 31% of greenery, minimum 4.3% of floor colour diversity, and safety contribute to creating a sense of amazement.
3. Vertical accessibility above 80% variation, with moderate density for the usage, especially a minimum of 15% of walls, more than 5% visible skyline, minimum 11% of

greenery, and 10% ceiling coverage are important classifications in creating a sense of amazement at the uppermost floor sky garden.

4. Permeability above 80% variation, with a minimum of 55% of walls for visible accessibility and walkability, less than 0.8% solid doors, a minimum of 5.3% of users' density, and more than 10% of openness for visible permeability.
5. Economic catchment between 20% and 40% variation, moderate depth with less than 43% columns within space, and minimum 8.5% ceiling coverage, more than 16.8% open skyline, and less than 6.7% of users' density create a sense of amazement at the uppermost floor sky garden.

7. Conclusions

The objective of this research was to assess participants' perceptions and emotional responses to specific elements of vertical and volumetric urban environments. From this assessment, three-dimensional vertical urban design guidelines based on cognitive measurement and modelling for Human Centre Design have been formulated.

In order to examine the micro-scale of an internal setting, this research analysed a 250 m high vertical and volumetric building typology. For the assessment, the participants were immersed in a viewing experience of "3D urban interior spaces" using virtual reality goggles. This experiment involved manipulating variables such as varying levels of sunlight, limited window views, and the inclusion of multiple layers of interior public spaces and open areas, which were presented through different stimuli on a screen.

In a broad sense, the findings derived from the EEG test, regarding the parameters and their variations, can be summarised as follows:

1. Increased emotional and cognitive responses are observed when there is exterior accessibility from outside to inside space at the ground level compared to interior accessibility at the ground level.
2. Active thinking and cognition are associated with mid-level interior spaces that require navigation using physical signage.
3. The presence of walkability levels exceeding 60%, with an abundance of elevators and pathway options, leads to increased interest and spatial cognition.
4. The uppermost floor with improved visibility and a heightened sense of safety triggers excitement and increased cognition.
5. A greater amount and variety of greenery at higher floors enhances positive cognition.
6. Spatial cognition is enhanced by an increased level of spatial permeability and legibility.
7. A higher cognitive response and reaction are observed with an increased level of diversity.
8. Changes in economic catchment generate excitement and heightened cognition.
9. Spatial cognition is influenced by changes in natural light levels.
10. Images that have a cultural reference and aesthetic evoke responses in both sensory processing and spatial cognition.

With these findings, this study successfully assessed the interconnected layers of interior public realms and open spaces and examined the emotional connections and responses associated with them. The evaluation, utilizing various parameters and their variations, demonstrated the potential for a generalised assessment tool to gauge users' emotional responses to diverse spatial conditions. These 10 findings were based on the EEG testing of cognitive responses to four variations based on the following nine parameters: greenery, accessibility, walkability, permeability, diversity, economic catchment, safety, light, and cultural identity/aesthetics. This highlighted the importance of a spatial network that was both walkable and with a good degree of visibility, easily accessibility from the street level to the interior public realm, making use of navigation systems to enhance walkability and permeability, including vertical permeability and the quality of both the visual and physical connections between floors to enhance walkability and accessibility. Cultural aesthetics and economic catchment are key parameters for the diversity and richness of spatial cognition, together with natural light and greenery at elevated levels.

In conclusion, the research established a neuroscientific framework that quantifies the influence of high-rise and volumetric urban environments on human cognition and overall experience.

These tools have equal applicability in practical scenarios for designers, planners, decision makers, and academics. They can be utilised to aid in the creation of responsive and efficient urban environments that cater to the needs of inhabitants within high-density vertical and volumetric urbanism.

While this research has focused on specific aspects, such as interior public realms and public spaces, it did not encompass various scales within multi-level structures, such as lift lobbies, staircases, and corridors. However, future research endeavours will aim to address this gap and provide a comprehensive and systematic dataset on emotional and spatial cognition related to vertical and volumetric urbanism.

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