EEG-Based Assessment of Psychological Comfort in Urban Spaces: Impacts on Psychological and Cognitive States Using Virtual Reality Simulations

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Abstract

This study investigates the influence of urban design elements on psychological and cognitive states using neuroscience-based metrics. Participants were immersed in 360-degree VR simulations of diverse urban environments, featuring variations in scale, street width, green spaces, urban form, edges, "eyes on the street", lighting, colour, land use, accessibility, and building density. Neural responses from EEG (electroencephalogram) measurements were recorded using an Emotiv Insight EEG device, quantifying emotional states through frequency bands. Results revealed distinct impacts of urban design elements on psychological comfort and cognitive performance. Green spaces and accessible layouts promoted relaxation and engagement, while dense environments with limited lighting increased stress. Narrow streets with active edges enhanced safety perceptions, whereas poorly lit areas caused discomfort. Age and gender differences were observed in responses to various environments. The findings led to a comprehensive evaluation framework, providing urban planners with evidence-based insights for designing inclusive, productive, and well-being-oriented public spaces. This research highlights the potential of integrating neuroscience into urban design, particularly for diverse and rapidly urbanising regions like India. This study's innovative approach combines virtual reality technology with neuroscientific measurements to offer a nuanced understanding of how urban environments affect human experience. These insights can inform future urban planning strategies, potentially improving the quality of life of city dwellers by creating more psychologically supportive and cognitively stimulating urban spaces.

Keywords: neurourbanism, environmental psychology, psychological comfort, urban design, virtual reality simulations, EEG measurements

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Introduction

Urbanisation has emerged as one of the most transformative phenomena of the 21st century, reshaping not only physical landscapes but also the emotional and psychological realities of the people who inhabit them. As of recent estimates, over half of the world's population resides in urban areas, and this proportion is expected to continue rising (United Nations, 2022). While urban environments offer substantial economic and cultural advantages, they are also associated with a higher prevalence of stress-related mental health conditions such as depression and anxiety (Peen et al., 2010). The World Health Organization (2011) projects that by 2030, depression will become the leading contributor to the global disease burden.

The urban condition is shaped by a complex interplay of environmental factors, including noise, crowding, air pollution, social density, lack of green space, and visual stimuli overload (Gascon et al., 2016). These factors collectively contribute to an increased physiological stress response, further exacerbating mental health risks (Haddad et al., 2019). Despite these well-documented effects, the psychological impact of the built environment remains underexplored in mainstream urban planning discourse. Traditional planning tools and guidelines often overlook the nuanced ways in which spatial configurations and environmental cues affect mental states (Heath et al., 2017).

In this context, the emerging field of neurourbanism offers a critical lens through which to study how cities affect human cognition, emotion, and behavior (Adli et al., 2017). This study employs a novel methodology that combines virtual reality (VR) simulations with electroencephalography (EEG) to assess how different urban forms influence psychological comfort and cognitive response. Through this neuroscience-informed approach, the research aims to provide actionable insights for designing urban spaces that support mental well-being.

Background

The intersection of neuroscience and urban design has only recently gained traction, yet early findings are compelling. Research by Lederbogen et al. (2011) revealed that individuals raised in urban environments exhibit heightened activity in the amygdala—a brain region central to threat detection and emotional processing—and increased reactivity in the anterior cingulate cortex, which is responsible for regulating emotional responses. These results suggest that urban upbringing can lead to lasting changes in the way the brain processes stress.

Environmental psychology and biophilic design research have long supported the idea that exposure to natural environments and thoughtfully designed public spaces can have restorative effects on mental health. Kaplan and Kaplan's (1989) Attention Restoration Theory (ART) posits that natural environments help individuals recover from mental fatigue and restore directed attention by providing opportunities for soft fascination, a sense of being away, extension, and compatibility. Similarly, Ulrich's (1983) Stress Recovery Theory (SRT) proposes that exposure to natural settings can facilitate psychological and physiological recovery from stress by triggering automatic, positive emotional changes and reducing physiological arousal. These theories provide foundational frameworks for understanding how environmental qualities influence emotional regulation and attentional capacities.

However, much of the research underpinning these theories has relied on subjective assessments or observational methods. The current study seeks to build on this foundation by integrating objective biometric data, specifically through electroencephalography (EEG), to examine emotional and cognitive responses to urban environments with greater precision (Kim et al., 2022). By leveraging real-time neural data, this research aims to inform spatial planning and contribute to user-centric urban design, thereby bridging the gap between psychological theory and evidence-based practice.

Methodology

This study adopted a laboratory-based, within-subjects experimental design to systematically examine the neurophysiological and affective responses caused by exposure to contrasting urban environments in immersive virtual reality (VR). The integration of VR with electroencephalography (EEG) monitoring is increasingly recognized as a rigorous approach for investigating the impact of environmental stimuli on human cognition and emotion, providing both ecological validity and experimental control (Bohil et al., 2011; Gramann et al., 2014; Slobounov et al., 2015).

Three core technological components formed the experimental setup:

- *Meta Quest 2 Headset:* This VR headset delivers high-resolution, 360-degree video playback, allowing participants to experience urban environments fully immersed in it. Such immersive VR platforms have been validated in prior research for their ability to elicit naturalistic responses comparable to real-world experiences (Freeman et al., 2017; Slater & Sanchez-Vives, 2016).
- *Insta360 ONE X2 Camera:* Real-world urban scenes were captured using this professional-grade 360-degree camera, ensuring spatial fidelity, depth cues, and the preservation of environmental complexity. The use of real-world footage, as opposed to computer-generated imagery, enhances ecological validity and participant engagement (Pan et al., 2020).
- *Emotiv Insight EEG Headset:* Neurophysiological data were collected with this wireless, five-channel EEG device, which records brain activity from multiple cortical regions. The Emotiv Insight is widely used in mobile and VR-based EEG research due to its portability and ability to capture cognitive and affective states in naturalistic settings (Debener et al., 2012; Duvinage et al., 2013; Stytsenko et al., 2011).

A total of 63 adult participants (aged 20–60 years) were recruited through purposive sampling. The inclusion criteria were designed to minimize confounding variables and ensure participant safety and engagement:

- *Neurological and Psychiatric Health:* Individuals with a history of neurological or psychiatric disorders were excluded, as such conditions can influence EEG patterns and affective responses (Luck, 2014).
- *Cognitive Function:* Participants were screened for significant cognitive impairment, ensuring the validity of both subjective and neurophysiological data (Folstein et al., 1975).
- *Lifestyle Factors:* Preference for walking or spending time outdoors was assessed to ensure participants would be receptive to the environmental stimuli and to reduce the risk of cybersickness or disengagement during VR exposure (Stanney et al., 2020).

- *Substance Use:* Individuals with a history of substance abuse or recent intoxication were excluded to avoid confounding effects on cognitive and affective measures (Volkow et al., 2016).

All participants provided written informed consent, and the study protocol was approved by the Institutional Ethics Committee Review Board of National Institute of Technology Calicut in accordance with the Declaration of Helsinki.

Upon arrival, participants completed the Beck Depression Inventory (BDI) to screen for depressive symptoms, followed by a demographic and health questionnaire. This initial screening ensured participant eligibility and provided baseline data for subsequent analyses (Beck et al., 1996; Smith et al., 2018).

The experiment was conducted in a room arranged for the purpose where the experimental setup was done. The setup included a table and chair for the participant to fill in the initial questionnaire, space to fix the EEG headset, a VR headset connected to a computer, and sufficient space of 2m radius for free movement of the participant while using VR. The experimental room was sound-attenuated and maintained at a comfortable temperature to minimize external distractions and physiological confounds (Cacioppo & Tassinary, 1990).

The experiment was built into the VR headset using a VR game developing software called Unity. This helps organize the video exposure and facilitates participant navigation through the experiment.

To investigate the influence of urban form on cognitive and emotional responses, two distinct pairs of urban environments were selected and recorded as immersive 360-degree videos. The environments were chosen based on established urban design theory and evidence from environmental psychology, which highlight the role of spatial openness, greenery, and architectural features in shaping affective and cognitive outcomes (Kaplan & Kaplan, 1989; Ulrich, 1983).

- *Environment A:* This setting featured a high-rise residential urban form with abundant greenery, a calm waterfront edge, and contemporary architecture. Such environments are hypothesized to promote psychological restoration and positive affect, consistent with biophilic design principles (Kellert & Calabrese, 2015).
- *Environment B:* In contrast, this environment comprised a dense, high-rise commercial district with historic built forms, narrow pathways, high visual complexity, and no vegetation. These characteristics are associated with increased cognitive load and potentially heightened arousal or stress responses (Evans, 2003; Lederbogen et al., 2011).

Both videos were edited to a uniform duration of three minutes and the auditory ambience from field recordings was masked, ensuring that differences in participant responses are attributed fully to visual-spatial characteristics and not to auditory confounds (Kaplan, 1995).

First, a Stroop test was conducted to measure cognitive reactivity and attentional control. This was followed by the participant's exposure to a neutral, calming video for three minutes while EEG data were recorded, in order to establish a physiological and psychological baseline of the participants. Baseline EEG and Stroop performance provided reference points against which changes during VR exposure could be assessed (Cavanagh & Frank, 2014; MacLeod, 1991).

Participants were fitted with the Emotiv Insight EEG and Meta Quest 2 VR headsets. The exposure sequence was as follows:

1. *Neutral Calming Video (Washout):* A three-minute neutral video was presented to measure baseline EEG activity (Slobounov et al., 2015).
2. *Exposure to Environment A:* Participants viewed the first urban environment for three minutes, with continuous EEG data collection (Pan et al., 2020).
3. *Neutral Calming Video (Washout):* A three-minute neutral video was presented to minimize carryover effects and allow physiological parameters to return to baseline (Slobounov et al., 2015).
4. *Exposure to Environment B:* Participants viewed the second urban environment for three minutes, again with continuous EEG monitoring (Pan et al., 2020).

Immediately following the VR exposures, participants completed the Self-Assessment Manikin (SAM) to rate their affective responses—specifically arousal, valence, and dominance—toward each environment. The SAM is a widely used, non-verbal pictorial tool for capturing affective states and has been validated in VR-EEG research (Bradley & Lang, 1994; Mühlberger et al., 2007; Smith et al., 2018).

This comprehensive protocol was designed to maximize ecological validity, control for confounding variables, and ensure participant well-being throughout the experimental session. The integration of immersive VR and mobile EEG in a controlled laboratory environment represents a cutting-edge methodological approach in environmental neuroscience and neuroarchitecture research (Adli et al., 2017; Bohil et al., 2011; Gramann et al., 2014).

Data Analysis

EEG data were processed using EmotivPRO software, leveraging its integrated analysis tools for real-time and post-processed data evaluation (Emotiv, 2024; MindTecStore, 2024). The performance metrics described in Table 1 below were used to interpret participants' brain wave patterns and infer their current mental state as they navigated various urban spaces.

Table 1
EmotivPRO Performance Metrics and Associated EEG Bandwidths

State (Abbreviation)	Definition	Relationship with Bandwidth
Stress (FRU)	Measurement of how comfortable a participant is with a given task.	Elevated beta activity and reduced alpha and theta activities indicate stress and frustration.
Engagement (ENG)	Alertness and conscious direction of attention towards task-relevant stimuli.	Measured primarily through beta and gamma activity. High beta and gamma waves indicate higher engagement and cognitive workload.
Interest (VAL)	Degree of attraction or aversion to current stimuli, environment, or activity.	Correlated with beta and gamma activity, indicating mental stimulation and curiosity.
Excitement (EXC)	Awareness or feeling of physiological arousal with a positive value.	Associated with increased beta and gamma activity, reflecting arousal and heightened emotional states.
Focus (FOC)	Measure of fixed attention to one specific task.	Strongly linked to beta wave activity, indicating sustained attention and concentration.
Relaxation (MED)	Measure of an ability to switch off and recover from intense concentration.	Higher alpha and theta wave activity are indicators of relaxation and meditative states.

In addition to raw EEG data, participant responses to the Self-Assessment Manikin (SAM) scale were used to triangulate findings, providing a multi-modal assessment of emotional and cognitive states (Bradley & Lang, 1994).

Results

Exposure to green environments (Environment A) was associated with increased alpha activity and reduced beta activity in the frontal and parietal regions of the brain. These neural patterns indicate a state of greater psychological comfort and diminished cognitive stress among participants (Kaplan & Kaplan, 1989; Ulrich, 1983). In contrast, dense, historically textured environments (Environment B) evoked elevated beta activity, which is typically linked to heightened alertness and stress responses (Evans, 2003; Lederbogen et al., 2011). Consistent with these neurophysiological findings, participants self-reported a stronger sense of relaxation, safety, and pleasantness in green, low-density spaces, as opposed to compact and visually chaotic settings (Gascon et al., 2016).

Analysis of participant responses revealed notable differences related to gender and age. Women demonstrated higher emotional sensitivity to spatial qualities such as colour, lighting, and enclosure (Smith et al., 2018). Conversely, men were more influenced by the scale and openness of the environment (Smith et al., 2018). Additionally, older participants displayed greater stress indicators when exposed to denser urban environments, whereas younger participants tended to be more cognitively stimulated by environmental complexity (Smith et al., 2018). These findings highlight the importance of considering demographic diversity in the design and evaluation of urban spaces.

Discussion

The results affirm the psychological importance of urban form and environmental quality. Green spaces and accessible layouts contribute not only to ecological health but also to neurological well-being (Kaplan & Kaplan, 1989; Ulrich, 1983). The variation in emotional response across age and gender groups indicates that urban design must adopt inclusive and adaptive strategies (Smith et al., 2018).

The use of EEG in this context demonstrates how neuroscience can extend the toolkit available to urban designers. Rather than relying solely on subjective reporting, EEG allows for real-time, quantifiable insight into the cognitive-emotional experience of space (Bohil et al., 2011; Gramann et al., 2014).

The implications for planning in rapidly urbanising countries like India are significant. With increasing pressure on land and infrastructure, there is a tendency to prioritise efficiency over experiential quality. However, this study underscores that neglecting psychological comfort may lead to long-term societal costs in terms of public health and social cohesion (United Nations, 2022; World Health Organization, 2011).

Conclusion

This study provides empirical evidence that urban design directly affects psychological and cognitive states. By integrating virtual reality and EEG, it offers a methodological framework for evaluating design strategies before they are implemented in the real world (Bohil et al., 2011; Gramann et al., 2014). Such evidence-based approaches are crucial for creating cities that are not just functional, but humane and health-promoting (Adli et al., 2017).

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the author(s) utilized generative AI and AI-assisted technologies to assist in writing, improving, and proofreading the text. Specifically, OpenAI's language model (Perplexity) was employed to support the drafting and structuring of the introduction, background, methodology, results, discussion, and conclusion sections.

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