Visual complexity, stress levels, and restorative environments: 1/f noise analysis for a better understanding of Intangible Human-Environment Interactions.

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Abstract

Humans and environments are intertwined through sensory experiences, with visual perceptions significantly impacting emotional and psychological states. Research has explored spatial visual complexity's role in image processing, cognitive load, and stress relief, as well as the positive effects of fractal properties on stress reduction and emotional responses. While fractal properties in natural landscapes are crucial for understanding visual complexity, they can be further analysed through the geometrical properties of spaces. By integrating 1/f noise analysis, the complexity of signals processed by the brain is further enhanced, offering significant potential for understanding 1/f noise's impact on visual perceptions, which remains underexplored in urban research. This study examines 1/f noise values and their effects on visual perceptions and physiological responses in various spatial complexities. In a pilot test, participants viewed images with different spatial complexities and 1/f noise values while their brain activity was monitored with an EEG device. The study aims to preliminary explore changes in live brain activity and note potential trends between stress levels, engagement, and attention focus across a limited range of 1/f noise values. The initial results of this study suggest the potential for larger-scale experiments to further investigate the impact of spatial complexity measures such as 1/f noise on brain activity using EEG, highlighting the ongoing need to refine urban design practices to better cater to the psychological needs of urban populations.

Keywords: *1/f noise, visual complexity, stress reduction, EEG, restorative environments*

1. INTRODUCTION

Humans experience their environments through various senses, and understanding the ways in which the sensations work together can be critical for designers to optimise the city from a strictly functional-based design to a perceptual restorative design paradigm. Researchers from related fields have extensively explored this topic, paying particular attention to vision and visibility analysis. The concept of 'visualism', which places vision at the top of a sensory hierarchy, often results in 'visual privilege', where visual information dominates interpretation. This notion has been frequently criticised in related works [1,2,3,4]. However, it is still valuable to learn more about vision, particularly in large-scale landscapes, since vision is the only sense capable of engaging with landscapes over long distances [2,5,6,7].

Visual perception has a strong connection with humans' emotional and psychological states. Researchers have found that the visual stimuli in cities affect people's stress levels and cognitive load [8,9,10]. On the other hand, fractal patterns in nature can make people feel less stressed and improve their emotional health [11,12,13]. In particular, fractal properties, as well as repeating patterns at different scales, were related to reduced physiological stress markers [14]. It has been proven that having a glance at natural elements, such as vegetation in parks, trees along the streets, and even plants throughout windows, can improve citizens' cognitive performance and reduce negative emotions [15,16].

For exploring the possible method to engage visual complexity as a factor in urban design, this study uses 1/f noise analysis as a visual complexity quantification parameter and electroencephalography (EEG) to understand the detailed relationship between visual stimuli and biological response. In the field of visual cognition and environmental studies, 1/f noise is a signal that represents a frequency spectrum where the power of the signal inversely correlates with its frequency [17]. Its characteristics include being self-similar and fractal [18]; the pattern looks similar and regular on all scales; it is usually found in natural environments; and it has been associated with aesthetic and psychological benefits [19,20,21,22,23]. EEG, a non-invasive method that measures brain activity, provides insights that enable researchers to observe how cognitive load impacts the brain's responses to external stimuli [24]. Our research tends to further explore the relationship between 1/f noise and brain activity in urban environments. Beginning an exploration towards the understanding of how different levels of visual complexity affect stress and cognitive responses and the way that 1/f noise as a parameter can contribute to designing urban spaces could be crucial to promoting well-being for better urban futures.

2. LITERATURE REVIEW

Spatial visual complexity is a pivotal concept in environmental psychology, visual cognition, and related interdisciplinary areas [8,25,26,27]. One of the most efficient ways to analyse visual complexity is through fractal dimensions. Researchers have found recurrent self-similar fractal structures in nature [26,28,29,30], which allow the studies to simplify and analyse the visual scenes from an infinite scale to a sizable portion of the whole scene. Consequently, researchers can have an overview of the brain response to the whole scene that shares the same fractal dimension, providing insights for understanding the hierarchical order of visual processing [31].

Electroencephalography (EEG) is a non-invasive technique that measures brain activity by placing electrodes on the scalp. It is a powerful tool that demonstrates brain activity with five basic brainwaves: Alpha (α), Beta (β), Theta (θ), Gamma (γ), and Delta (δ), that are categorised by different frequencies and brain states [32]. In the visual-environmental related fields, there are many studies that have proved the efficiency and precision of using EEG and fractal dimensions to analyse the human biological response to environments, focusing on understanding the visual stimuli, complexity, and cognitive process [33,34,35]. Specifically, Dorosti and Khosrowabadi have investigated the fractal dimension of EEG signals, giving insight into the fluctuation between visual complexity and the fractal dimension and their proportional relationship with the significant brain activities in the centre-parietal and parietal regions [35]. Namazi et al. [33] and Namazi [34] also supported the statements about the visual-cognitive relationship made by Dorosti and Khosrowabadi [35], with further research on the relationship between fractal patterns in stimuli and their impact on fixational eye movements and EEG signals. Additionally, Purcell et al. [36], Joye [37], Joye & Berg [38], and Hägerhäll et al. [39] describe the evolution of using EEG and fractals as methods for analysing environments.

The discussions focus on the roles of fractal patterns in shaping aesthetic preference [36], how EEG responses to exact and statistical fractal patterns [37], and the significance of fractal patterns in nature and natural elements with their physio-psychological benefits [36,37,38,39].

In relation to environmental studies, Ulrich's psychophysiological framework emphasises the significance of complexity in shaping human preferences for natural environments [30]. Ulrich utilised Kaplan's evaluative matrix with components like coherence, mystery, and preference, demonstrating that the cognitive load is directly impacted by visual complexity. In comparison with urban environments, natural scenes are typically less visually complex and more restorative as they reduce the cognitive load [29]. Further, Cooper et al. find that the fractal dimension of streetscapes affects perceptions of quality and engagement. Suggesting that engaging the vegetation in the urban environment can enhance the aesthetic quality of streets and positively contribute to residents' perceptions and well-being [25]. Valtchanov and Ellard, on the other hand, used the fractal dimension to analyse the complexity of a natural scene, finding that natural scenes can enhance cognitive engagement while reducing cognitive load [8].

By connecting the fractal dimension with visual complexity, studies found that higher visual complexity can make environments more interesting, engaging, and stimulating for observers; however, it requires a higher cognitive load with less restorative perception, which might lead to a higher level of stress and intensify the possibility of negative mental issues [24,29,30,31].

Given the potential that fractal dimensions have shown in past studies in broadening our understanding of spatial visual complexity, with this study we explore another parameter, founded on the same grounds of fractality taken as a quantification of visual complexity. This parameter is called 1/f noise, otherwise referred to as 'pink noise'. Mathematically, it produces a line in a log-log spectral plot with a slope approaching -1, indicating the presence of a scale-invariant scaling relationship that is typical of fractal structures [40]. Some studies have investigated using 1/f noise as a method to analyse the urban environment [41,42,43]. Le et al., for instance, noted the visual discomfort in urban scenes [41]. They have found that in modern urban environments, the unnatural 1/f noise stimulates large amounts of hemodynamic responses in the visual cortex. Meanwhile, in Flitcroft et al.'s studies, they compare both indoor and outdoor scenes in the urban area with the natural scenes, with the same findings as with 1/f noise analysis that urban scenes require a higher cognitive load and increase visual discomfort, which leads to a higher development of myopia in cities [43].

This study will focus on some urban typologies to explore possible reactions of brain activity to 1/f noise ranges. Carmona's works deliver a comprehensive understanding of typology as an advanced classifying method that considers physical attributes with design, functional perspective, social interaction, and management practice [44,45,46].

Current studies on the relationship between visual stimuli, 1/f noise, and cognitive and psychological processes lack statistical correspondence with bio-signal data [41,42]. Besides, there is a need for methodologies that integrate urban design and neuroscience to underpin this topic and explore more in-depth 1/f noise as a parameter for designing restorative urban environments [41,43]. In this study, we begin some exploration of possible relationships between visual complexity and brain activity through the integration of 1/f noise analysis, images as visual stimuli, and EEG responses. The research is hoping to set the groundwork for exploring 1/f noise potentials as a parameter in designing restorative urban environments.

3. METHODS

3.1 Data collection on-site and image selection

The image collection was based in Shenzhen. On a single day, under consistent weather conditions, we used a Sony 6400 camera equipped with a tripod to maintain a viewing height of 1.60 m. A total of 592 urban street scene photographs were taken at an approximate focal length of 50 mm using a zoom lens. These images were then rigorously screened, resulting in the selection of 502 photos with focal lengths between 45–55 mm. These photos were manually classified into five urban typologies typically found in Shenzhen: urban parks, urban streets, housing estates, shopping malls (indoor and outdoor), and science and technology parks.

3.2 Experiment Design

The experiment was conducted in a controlled dark room environment (Figure1), with a large screen measuring 1.904 metres in width and 1.071 metres in height used as the display device. The centre of the screen was positioned at a height of 1.60 m. We conducted the experiment with 8 participants from the Southern University of Science and Technology. During the experiment, the 11 selected images were displayed randomly, with a neutral grey image serving as an interval. Each participant was exposed to each image, and brain activity was recorded as a reaction to the visual exposure. We employed an EMOTIV EPOC X, a 14-channel wet sensor EEG device, to record brainwave activity in the theta (3–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–100 Hz) frequency bands. The Fast Fourier Transform (FFT) was used to obtain the spatial frequency power intensity for each band. Invalid high-frequency and low-frequency information was filtered out, and fitting calculations were performed to determine the slope of the power spectrum.

Figure 1. Snapshots from the experiment.

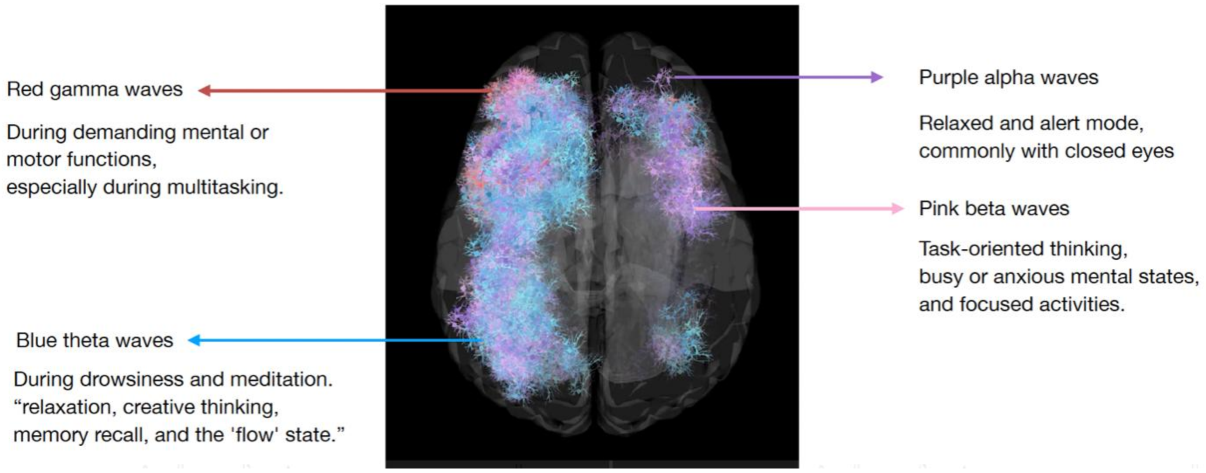

Figure 2. Snapshot of recorded brain activity and corresponding colours for each frequency.

3.3 Data processing: 1/f noise and brain activity

To calculate the 1/f noise value, images first undergo conversion to grayscale, followed by the application of a discrete Fourier transform to transition the grayscale values from a spatial representation to their frequency components. By squaring the absolute values of the Fourier transform, the power spectrum is obtained, which quantifies each frequency component's contribution to the image's structure. The 1/f noise value is derived from the slope of the log-log plot of frequency versus amplitude, focusing on the frequency range between 2 and 80 cycles to emphasise the frequencies that most significantly represent structural information in the image. (Figure 3). For brainwaves, the real-time high-precision brainwave frequency data were segmented into eleven 25-second periods (including both test and rest phases) and eleven 15-second periods (eyes-open test phases only). The peak, trough, and average values of the four types of brainwaves were then obtained, and these values were averaged across eight groups of data. To obtain these data, we employed the HSL colour model to extract the brainwave signals corresponding to four colours (each colour corresponding to one of the four frequencies detected by the EEG measurement), frame by frame (Figure 2). The sum of the amplitudes of the four types of brainwaves in the frame with the largest overall amplitude was set to 100%, and the amplitudes of other frames were proportionally mapped.

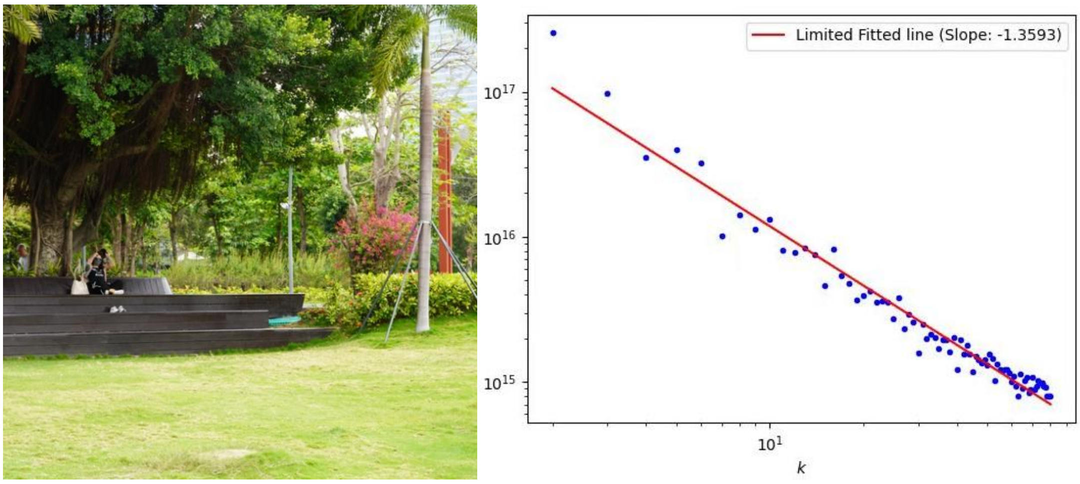

Figure 3. Image 01 (urban parks) and related 1/f noise diagram.

4. RESULTS

The comparison between 1/f noise slope values and specific brainwave patterns has yielded insightful results with different urban environment types (urban parks, shopping malls, science and technology parks, urban streets, and housing) eliciting distinct physiological responses (Table 1).

Housing features the steepest 1/f slope values (-1.275 and -1.414), which indicate lower visual complexity, and also has higher theta proportions (mean theta proportion: 38.4%) associated with relaxed and creative states and lower beta proportions (mean beta proportion: 1.9%) indicating lower cognitive effort.

Urban Street images represent flatter 1/f slope values (-1.07 and -1.14) and exhibit lower theta values (mean theta proportion 34.6%), indicating less relaxation, but also lower gamma (mean gamma proportion 0.006%), indicating lower cognitive load.

The Science and Technology Park images represent a wide range of 1/f slope values (-0.98 and -1.27) but consistently feature the highest gamma proportion (mean gamma proportion 1.1%), suggesting these environments require more cognitive effort and alertness.

Table 1. Table of 1/f and EEG calculation result

Type	Image	1/f noise	theta_Average	gamma_Average	alpha_Average	beta_Average
Urban parks	01	-1.359	40.209	0.012	33.572	2.345
	10	-0.982	36.120	0.006	25.736	1.799
Shopping malls	02	-1.286	36.869	0.007	34.196	2.852
	07	-1.119	33.362	0.008	30.890	1.789
I-Parks	03	-0.985	38.020	0.011	30.100	2.278
	09	-1.265	33.191	0.011	30.989	2.646
Urban streets	04	-1.072	33.056	0.007	31.577	2.339
	08	-1.141	36.154	0.005	27.193	2.315
Housing	05	-1.275	37.531	0.009	31.175	1.958
	11	-1.414	39.360	0.006	28.480	1.884

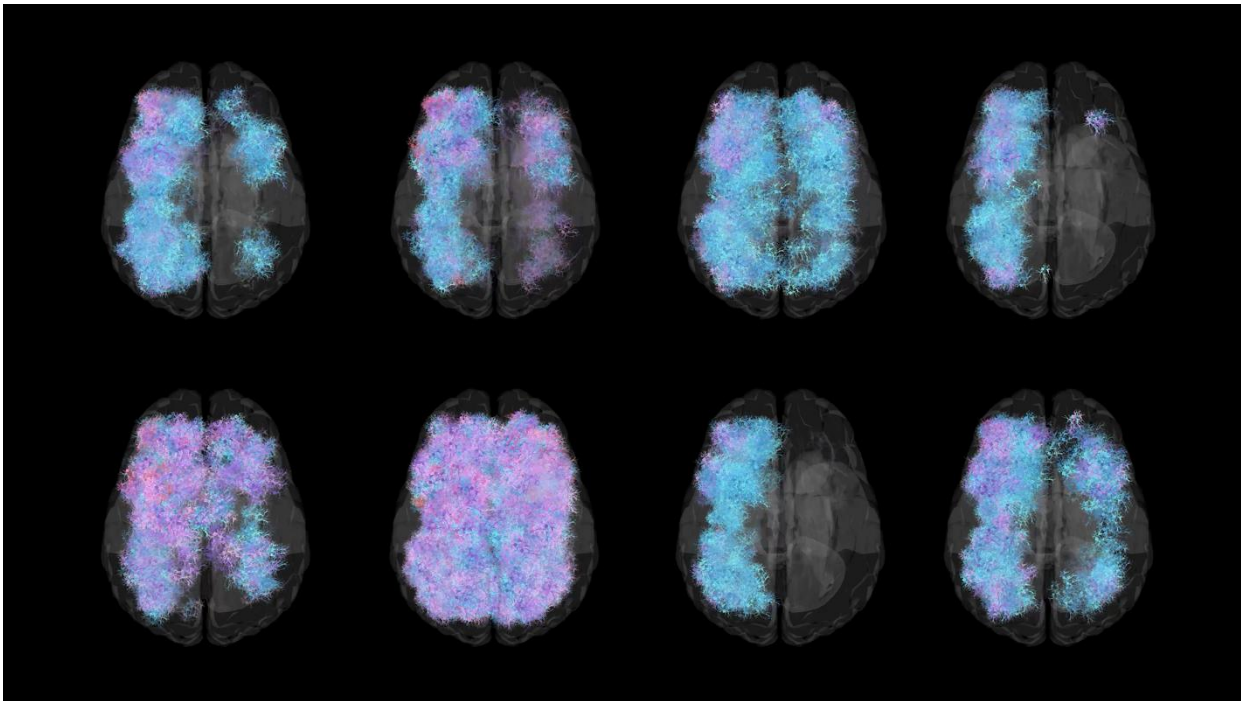

Figure 4. Screenshot of brainwaves recorded during the experiment. The 8 participants were individually looking at the same image (source: the authors).

5. DISCUSSION

This study investigates the possible role of 1/f noise in shaping human perceptions in urban environments. The study of physiological responses to different levels of spatial complexity through EEG data offers a unique window into how human brains interact with their visual environments (Figure 4). By correlating these responses with specific types of visual stimuli, we can draw deeper insights into the cognitive and emotional effects of spatial complexity.

We ask the question of whether environments that mimic the fractal patterns found in nature can help reduce stress and promote mental health. This study takes some tentative steps to expand upon existing literature that links naturalistic elements in urban settings with reduced stress and increased cognitive engagement. The exploration relates to how spaces designed with complexity similar to natural environments could facilitate cognitive restoration and stress reduction more effectively than monotonous urban landscapes; however, a lot more research is needed to corroborate this.

The study acknowledges limitations, such as the controlled setting of the experiment, which may not fully capture the complexity of real-world environments. Additionally, the sample size and demographic homogeneity could bias the results, limiting their generalizability.

Future research should aim to replicate these findings in more diverse and dynamic urban settings to enhance their applicability. Longitudinal studies could also explore the long-term effects of exposure to environments with varied 1/f noise levels. Expanding the demographic breadth and incorporating multidisciplinary approaches could provide a more comprehensive understanding of how urban design influences human health and well-being.

6. CONCLUSION

The initial results observed in this study show potential for conducting a larger-scale experiment to investigate the relationship between special complexity measures, like 1/f noise, and the impact on brain activity as measured with an EEG device. The study moves towards investigating the importance of considering sensory inputs in the design of urban environments.

Ongoing research is crucial to further discern how different special complexity measures, like 1/f noise, and other design elements affect human health and behaviour. Continuous study will help refine urban design practices to better meet the psychological needs of urban populations for better futures.

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Ethical considerations

Ethical approval was obtained by the Medical Ethics Committee of the Southern University of Science and Technology and the School of Design of the Southern University of Science and Technology.

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