Enhancing Social Interaction in Urban Spaces: The Role of Vertical Greening Systems in High-Density Areas

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Abstract: The critical role of nature exposure in fostering prosocial behaviour and social connectedness is well-established in existing research, while intensifying urbanization presents growing challenges to the development of the nature in urban areas. The Vertical Greening System (VGS), an innovative approach that conserves land, emerges as a creative solution. However, its potential in enhancing social interactions remains under-explored. To bridge this gap, experiments were conducted to assess the impact of VGS on improving spatial quality, enhancing space attractiveness, and increasing pedestrians' willingness to walk, stay, and engage in social interactions. Results indicate that VGS serve as important visual attractors ang significantly enhances the visual attractiveness of urban spaces, leading to improved perceptions of environmental quality. This enhancement positively affects the affective experience of pedestrians, creating a more inviting atmosphere conducive to walk, stay, and socialize. Eye-tracking data shows that green elements serve as important visual attractors, suggesting that their strategic placement in urban design is critical to promoting social interaction.

Keywords: Vertical greening system, Environmental perception, Affective experiences, Social interaction.

1 Introduction

Continues urbanization has shaped oppressive streetscapes, leading to increased urban population and pressures of city life. The perceived overcrowding and increasing exposure to environmental stressors can significantly diminish individuals' evaluations of the built environment and their willingness to engage in outdoor activities. This, in turn, adversely affects both physical and mental health and reduces opportunities for social interaction, which are crucial for societal health(Zijlema et al., 2024, Luo and Jiang, 2022, Eizenberg and Jabareen, 2017).

The critical role of nature exposure in fostering prosocial behaviour and social connectedness is well-established in existing research. Nature environments not only provide necessary relief from urban stress but also serve as catalysts for social interaction by offering welcoming and livelihood communal spaces for gatherings and recreational activities(Hartig et al., 2014, Kaźmierczak, 2013).

However, intensifying urbanization presents significant challenges to the development and maintenance of natural environments within urban areas, leading to their decline and uneven distribution across cityscapes. Additionally, changes in lifestyle and the accelerated pace of modern life increasingly restrict the time people spend in nature. As Fuller and Gaston (2009) noted, interactions between urban residents and nature are increasingly mediated by informal green spaces, such as streetscape greening and pocket gardens, rather than traditional, large green networks.

In this context, the Vertical Greening System (VGS) emerges as an innovative solution that conservatively uses land while integrating accessible green infrastructure within high-density areas. Several empirical and experimental studies have highlighted the psychophysiological benefits of VGS in urban settings(Chan et al., 2021, Elsadek et al., 2019). Also, the potential of VGS to enhance the attractiveness of urban spaces, increase footfall, and promote social interactions has garnered increasing attention(Goel et al., 2022), while it remains under-researched and requires further scientific validation.

To address the existing knowledge gap, this study utilized a virtual reality (VR) experiment to evaluate the effects of various streetscape scenes, featuring different coverages of VGS, on individuals' environmental perception, affective experiences, and behaviours. The primary research questions explored were: 1) How does VGS in high-density open spaces affect perceived environmental quality and visual attraction? 2) How does VGS influences pedestrians' affective experiences in urban settings? 3) Does vertical greening enhance pedestrians' willingness to walk, stay, and participate in social activities within these environments?

2 Methods

2.1 Experiment design

A total of 5 streetscape VR scenes were created, each featuring the same building form but varying coverages of VGS, as detailed in Table 1. Each scene comprised 6 panoramic photographs rendered from different positions along the street model to comprehensively depict the street's characteristics. Each photograph was displayed for one minute and shown twice in VR experiment, as shown in Fig.1. Finally, rendered sequence frame images were used to create five 40-second streetscape video segments for post-experiment surveys.

Table 1. Characteristics of streetscape scenes in the 5 experimental groups(G) and 5 videos(V).

Experiment groups	G1/V1	G2/V2	G3/V3	G4/V4	G5/V5
Coverages of VGS in VR scenes (%)[1]	0	8	16	32	48

[1] The coverage of VG in streetscape scenes was quantified by calculating the percentage of the façade covered by VGS relative to the total façade area of the street block.

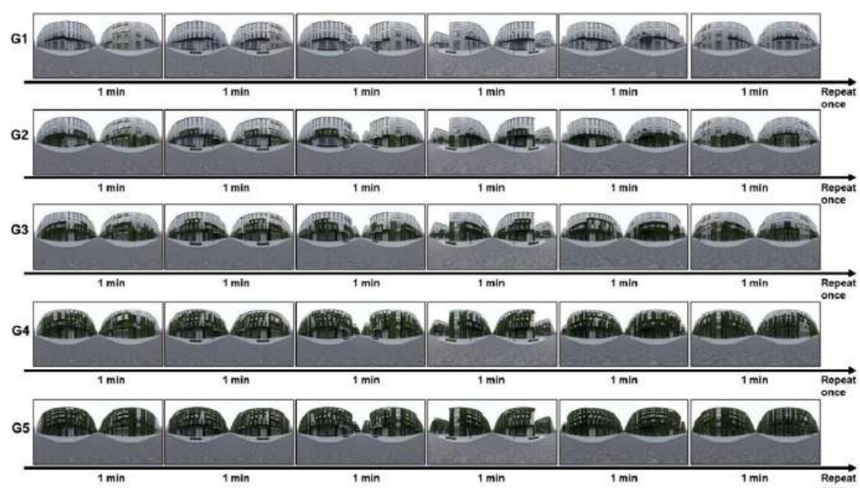

Fig.1. VR experimental stimulation design.

2.2 Participants

We recruited 30 healthy adults from Tongji University to participate in the study. Eligibility criteria required participants to be aged between 18 and 35. Individuals who had consumed tobacco, alcohol, drugs, or caffeinated beverages within 24 hours prior to the experiment, or who had engaged in intensive exercise within 6 hours of the experiment, were excluded. The study received approval from the Science and Ethics Committee of Tongji University, and all participants provided written informed consent before participating.

Prior to the experiment, we collected data on participants' socio-demographic background, chronic mental stress levels, nature connectedness, noise sensitivity, and other relevant covariates through a questionnaire. Participants were then approximately assigned to one of five experimental groups based on their survey responses, allowing for a rough control of these covariates across the groups. The descriptive statistics of their background information are presented in Table 2, and there were no statistically significant differences between 5 VR experiment groups.

Table 2. Descriptive statistics of the participants' background information.

Measures		**Participants Mean (± SD) or Number (percent, %)**					
		G1	**G2**	**G3**	**G4**	**G5**	**V1 to V5**
Gender	Male	4	3	3	3	3	16
	Female	2	3	3	2	3	14
Education	Bachelor	3	2	4	3	4	16
	Master	1	3	2	2	2	11
	Doctorate	2	1	0	0	0	3
Place of upbringing	Central urban district	4	3	2	3	2	15
	Suburbs or townships	2	2	4	2	4	14
	Rural area	0	1	0	0	0	1
Nature connectedness[1]		4.9 (±0.8)	5 (±1.31)	5.3 (±0.84)	5.4 (±0.67)	5.5 (±0.54)	5.27 (±0.85)
Noise sensitivity[2]		92.5 (±6.8)	88.5 (±18)	91.5 (±11)	78.6 (±12.8)	99.3 (±14)	91 (±14)
Chronic mental stress levels[3]		17.5 (±5)	14.2 (±6)	13.7 (±4.8)	12.2 (±7.7)	15.0 (±8.4)	15 (±6)

[1] **Nature connectedness**, describes a psychological state where individuals deeply care for and feel connected to nature, reflecting their innate biophilic tendencies(Capaldi et al., 2014). It serves as an indicator of the extent to which these tendencies are fostered or suppressed(Nisbet and Zelenski, 2013). Research shows that nature connectedness affects, moderates, and mediates the impact of nature exposure on mental health(Liu et al., 2022). In this study, we used 6-iterm and 7-point Nature-Relatedness Scale to measure an individuals' nature connectedness(Gong et al., 2024).

[2] **Noise sensitivity**, which refers to an individual's susceptibility and degree of reaction to everyday noises, was evaluated using the Weinstein Noise Sensitivity Scale (WNSS) in this study(Weinstein, 1978).

[3] **Chronic mental stress levels**, which have been shown to influence the mental effects of nature exposure on individuals(Shanahan et al., 2015), were assessed using the Perceived Stress Scale (PSS-10) in this study(Cohen et al., 1983).

2.3 Procedure

As illustrated in Figure 2, the experiment comprises three phases: preparation, testing, and post-testing.

In the preparation period, participants signed written informed consent and were equipped with the VR devices and biomonitoring sensors. Participants were then asked to close eyes and rest for 3 minutes while electro-dermal activity (EDA) data recording commenced. Subsequently, participants completed a self-reported scale to establish psychological baselines.

During the testing period, participants were divided into five groups and randomly assigned to one of five VR scenes. Initially, they were exposed to traffic noise for 5 minutes and completed a self-reported scale. This was followed by a 12-minute viewing of a VR scene along with the collection of eye-tracking data, after which they filled out the same self-reported scale again. Upon completion, all devices were deactivated and removed, and participants rated their level of discomfort during the VR test using a 5-point Likert scale (1 = very slightly or not at all, 5 = extremely).

After VR testing, participants were required to complete post-test surveys. They viewed five videos through an online link and immediately assessed perceived oppressiveness, environmental quality, visual preference, affective experience, and their willingness to engage in various outdoor activities in such environment. The videos were presented in a random order to prevent any sequence effects.

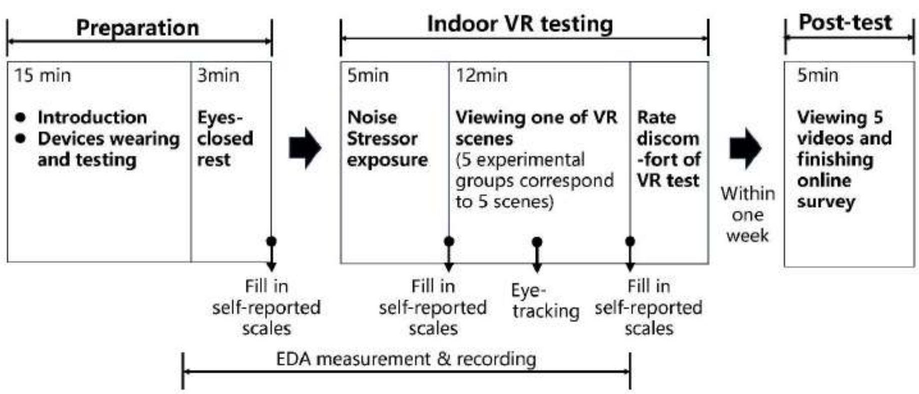

Fig.2. Experimental procedure.

2.4 Measures

2.3.1 Perceived oppressiveness and perceived environmental quality

Perceived oppressiveness (PO) is the subjective experience of feeling overwhelmed or dominated by a physical environment, negatively related to urban environmental quality(Asgarzadeh et al., 2012). Perceived environmental quality (PEQ) involves the subjective evaluation of a physical environment, encompassing an individual's multisensory perception of various environmental attributes. Both PO and PEQ have been identified as mediators in the relationship between an individual's environmental exposure and their psychophysiological responses and behaviours (Luo and Jiang, 2022).

We assessed participants' PO and PEQ in response to online videos by asking, "Do you feel oppressiveness?" and "How would you rate the visual quality/ safety level/ economic level of the street environment depicted in the video?", respectively. An 11-point VAS, ranging from 0 (very low) to 10 (very high), was utilized for these evaluations.

2.3.1 Visual attractiveness

Self-reported visual preferences for online streetscape videos and eye-tracking data collected during VR testing were used to assess the visual attractiveness of the scenes. After viewing the five streetscape videos, participants were asked to rank the videos on a 5-point scale from 1 to 5, where 1 indicates the least liked and 5 indicates the most liked, with scores increasing progressively based on preference. Additionally, eye-tracking data was utilized to analyse visual attention and identify hotspots within the visual stimuli.

2.3.3 Affective experience: psychological and physiological

As detailed in Table 3, the Self-Assessment Manikin (SAM) was employed to assess individuals' affective states through 9-point valence (from 1-unpleasant to 9-pleasant). In addition, individuals' physiological responses were measured using Skin Conductance Level (SCL), which represents individuals' arousal and stress level.

Table 3. Psychological and physiological measures.

Psychological and physiological measures		Description	Relationship with the stress level
SAM	Valence	Affective states	-
EDA	SCL (μS)	Arousal and stress level	Positive

2.3.4 Measures of outdoor behaviours

To measure individuals' outdoor behavioural intent, we asked participants, "How willing are you to visit, walk, stay, or engage in social activities in the street depicted in the online video?" We utilized an 11-point Visual Analog Scale (VAS) for responses, ranging from 0 (not at all willing) to 10 (very willing).

2.5 Statistical analysis

Environmental perception data, including self-reported Perceived Oppressiveness (PO), Perceived Environmental Quality (PEQ), visual preference, and behavioural intent, were collected via a within-subject online survey. Differences in environmental perception and intent data across the five online videos were compared using one-way repeated measures ANOVA for normally distributed data and the Friedman test for non-normally distributed data.

The affective psychophysiological data collected from a between-subject VR experiment design were analysed using one-way ANOVA for normally distributed data and the Kruskal-Wallis H test for non-normally distributed data to compare differences across five VR groups. Additionally, two-way ANOVA models with post-hoc pairwise comparisons were conducted to examine per-minute Skin Conductance Level (SCL) responses to the five VR scenes.

All data were presented as means, and for all comparisons, a p-value of less than 0.05 was considered statistically significant.

3 Results and discussion

3.1 Perceived oppressiveness (PO) and perceived environmental quality (PEQ)

As shown in Figure 3, the post-hoc tests indicated that the PO of V1, which had no VGS coverage, was significantly higher compared to V2 and V3. Conversely, the Perceived Environmental Quality (PEQ) of V1 was significantly lower than that of V2, V3, V4, and V5. This suggests that VGS can significantly enhance people's perceptions of street quality and reduce the oppressiveness of high-density streetscapes. However, it is important to note that when VGS coverage is excessively high, as in V4 and V5, the beneficial effects of reducing perceived oppressiveness in high-density streetscapes may diminish. As shown in Figure 4, the relationship between VGS coverage and PO is depicted by a U-shaped curve. Conversely, the relationship between VGS coverage and PEQ is represented by an inverted U-shaped curve.

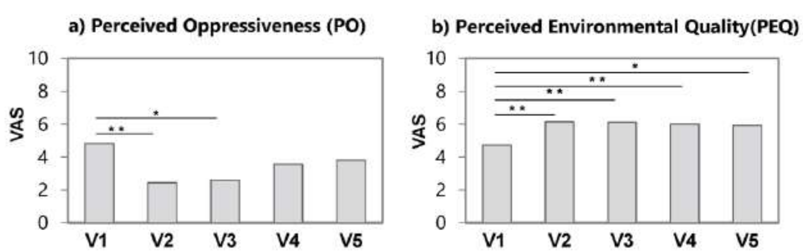

Fig.3. Participants' PO and PEQ across 5 streetscape videos, *p < 0.05, **p < 0.01, ***p < 0.001.

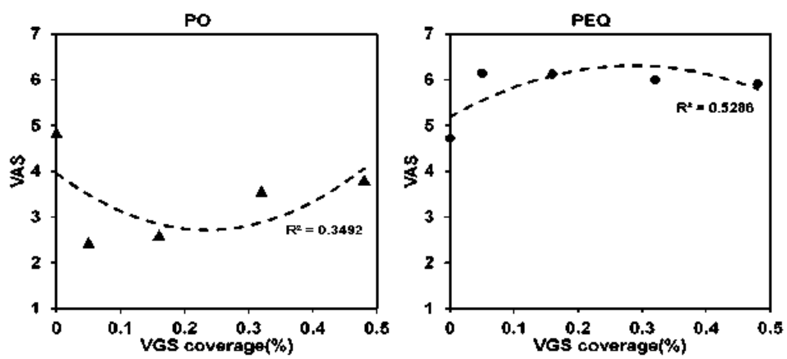

Fig.4. Patterns between VGS coverage and participants' PO & PEQ.

3.2 Visual attractiveness: visual preference and eye-catching factors

As shown in Figure 5, the coverage-response curve between VGS coverage and individuals' visual preference is depicted by an inverted U-shaped curve. Significant differences were observed in participants' visual preferences across five online streetscape videos with varying levels of VGS coverage. Specifically, preferences for V1, which had no VGS coverage, were lower compared to those with VGS coverage in V2, V3, V4, and V5. Statistically significant differences were noted between V1 and V2, V3, and V4. V3, which had the highest visual preference scores, also showing a statistically significant difference from V5, which had the second-lowest scores.

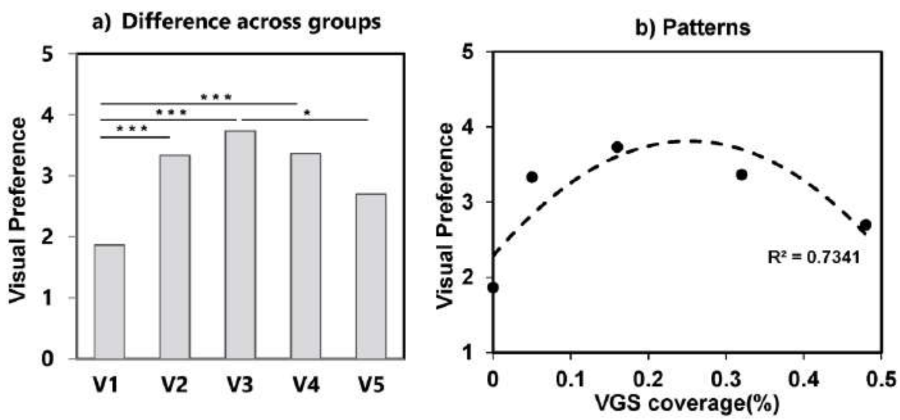

Fig.5. Participants' visual preference across 5 streetscape videos and its relationship with VGS coverage, *p < 0.05, **p < 0.01, ***p < 0.001.

After VR testing, eye-tracking hotspots were generated for five VR scene groups, namely, G1 to G5. As illustrated in Figure 6, participants in groups G1 (with no VGS) and G5 (with very high VGS coverage) tended to look straight ahead. They reported feeling oppressed by facades either devoid of greenery or heavily covered in greenery, mentioning that looking forward allowed them to see more sky. Conversely, in groups G2, G3, and G4—where vertical greening coverage was moderate—participants often turned their heads to appreciate the street facades, especially in G2 and G3, which had higher visual preference scores. This suggests that moderate VGS coverage can significantly enhance the visual appeal and of street facades.

G1 G2 G3 G4 G5

Fig.6. Participants' eye-catching factors across 5 VR scenes.

3.3 Affective experience

In this study, we utilized traffic noise to simulate the mental stress commonly experienced by pedestrians in high-density urban areas, where exposure to environmental stressors like heat and noise is prevalent. We specifically investigated how streetscapes with varying levels of VGS coverage influence the affective experiences of pedestrians after these stressor exposures.

Changes in psychological data (*Δ*Valence) and physiological data (*Δ*SCL) before and after experiencing VR scenes were used to assess the effects of VGS on the affective states of stressed participants. *Δ*valence and *Δ*SCL were calculated using equations (1) and (2) respectively and are summarized in Table 4.

Table 4. Measures of the effects of VGS on participants' affective state

Measures	Calculation

⊿Valence	(1) ⊿Valence = Valence $_{scene\ experience}$ - Valence $_{noise\ experience}$ "+" represents affective improvement
⊿SCL (μS)	(2) ⊿SCL = SCL $_{scene\ experience}$ - SCL $_{noise\ experience}$ "+" represents arousal and stress Increasing

3.3.1 Physiological data

Our analyses using paired t-tests and Wilcoxon signed-rank tests indicate a significant increase in participants' physiological stress levels following noise exposure. Additionally, ANOVA results reveal no statistically significant differences in physiological data among the five groups after exposure to the stressor. Participants' mean ⊿SCL across five groups during are displayed in Figure 7and Figure 8. As Figure 7 indicates, statistically significant differences in ΔSCL across VR scenes begin to manifest after 6 minutes of exposure. Consequently, as illustrated in Figure 8, we compared the average ΔSCL after 6 minutes. The post-hoc tests reveal that the ΔSCL of G1 was significantly higher than those of G2, G3, and G4. The relationship between VGS coverage and ΔSCL is characterized by a U-shaped curve, suggesting that moderate VGS coverage can significantly enhance pedestrians' affective states.

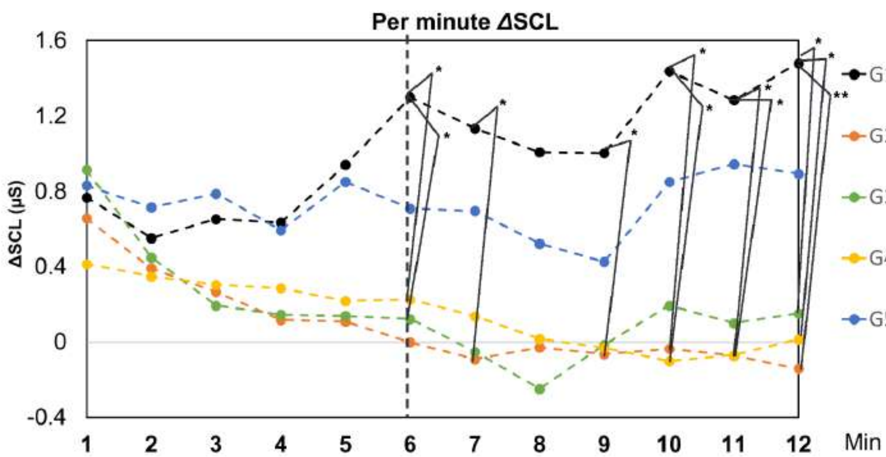

Fig.7. Pairwise comparisons of the estimated marginal means of per minute ⊿SCL during VR scenes experiencing. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

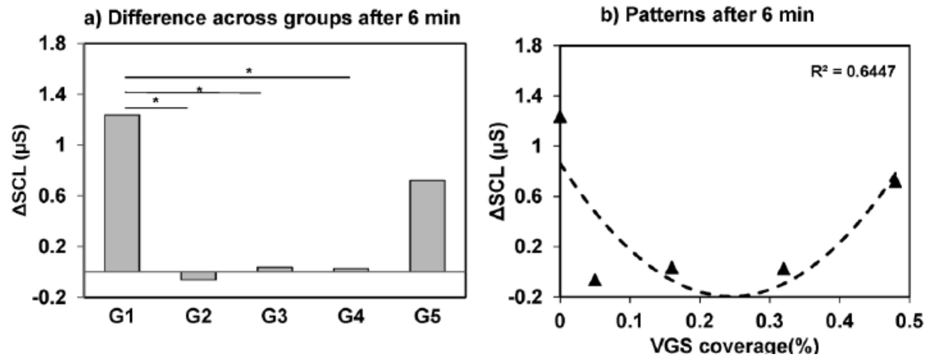

Fig.8. Patterns between the VGS coverage and participants' physiological response, *p < 0.05, **p < 0.01, ***p < 0.001.

3.3.2 Psychological data

As shown in Figure 9, although there were no statistically significant differences of psychological data. comparison between scenes still reflected important trends. The relationship between VGS coverage and Δvalence is characterized by an inverted U-shaped curve.

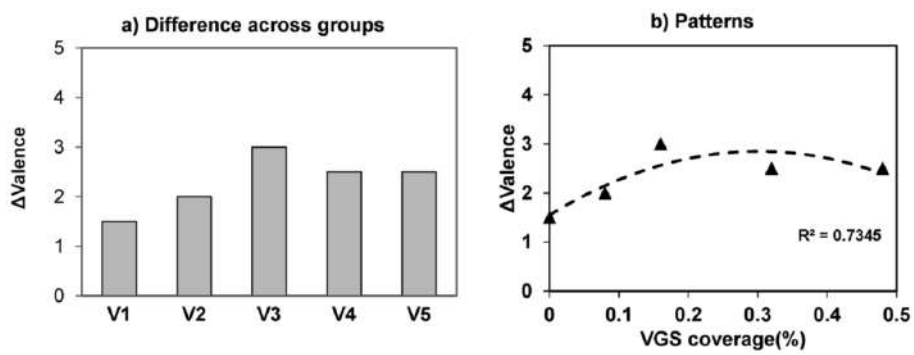

Fig.9. Participants' psychological effect across 5 streetscape videos and its relationship with VGS coverage, *p < 0.05, **p < 0.01, ***p < 0.001.

3.4 Outdoor behavioural intent

As depicted in Figures 10 and 11, individuals' willingness to visit, walk, and stay in V1 was significantly lower compared to V2, V3, and V4. Furthermore, the willingness to socialize in G1 was significantly lower than in V2 and V3. The relationship between VGS coverage and individuals' outdoor behavioural intent is characterized by an inverted U-shaped curve, indicating that both very low and very high levels of VGS coverage may decrease the desire to engage in outdoor activities, with moderate levels proving more conducive to positive behavioural intentions.

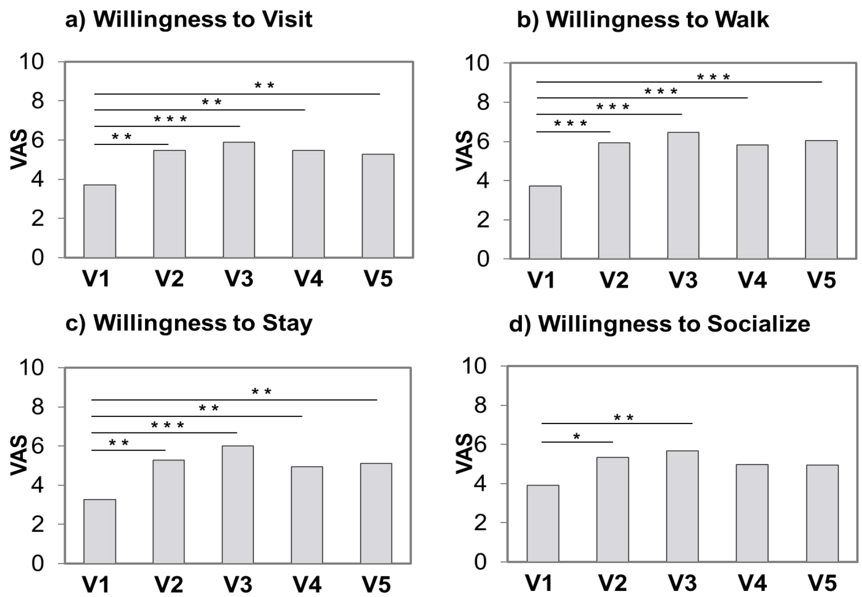

Fig.10. Participants' outdoor behavioural intent across 5 streetscape videos, *p < 0.05, **p < 0.01, ***p < 0.001.

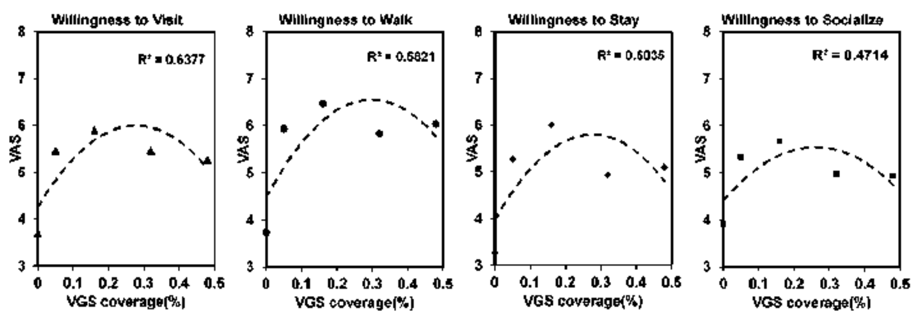

Fig.11. Patterns between the VGS coverage and participants' outdoor behavioural intent.

4. Conclusion

This study investigated the potential of VGS to enhance the attractiveness of urban spaces and promote social interactions. Results indicate that VGS serve as important visual attractors ang significantly enhances the visual attractiveness of high-density urban spaces, leading to improved perceptions of environmental quality. This enhancement positively affects the affective experience of pedestrians, creating a more inviting atmosphere conducive to walk, stay, and socialize. The relationships between VGS coverage and individuals' visual preference, perceived environmental quality and their outdoor behavioural intent are characterized by an inverted U-shaped curve, The relationship between VGS coverage and individuals'; the relationships between VGS coverage and individuals' perceived oppressiveness and stress level ware characterized by an inverted U-shaped curve. Eye-tracking data shows that green elements serve as important visual attractors, suggesting that their strategic placement in urban design is critical to promoting social interaction.

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