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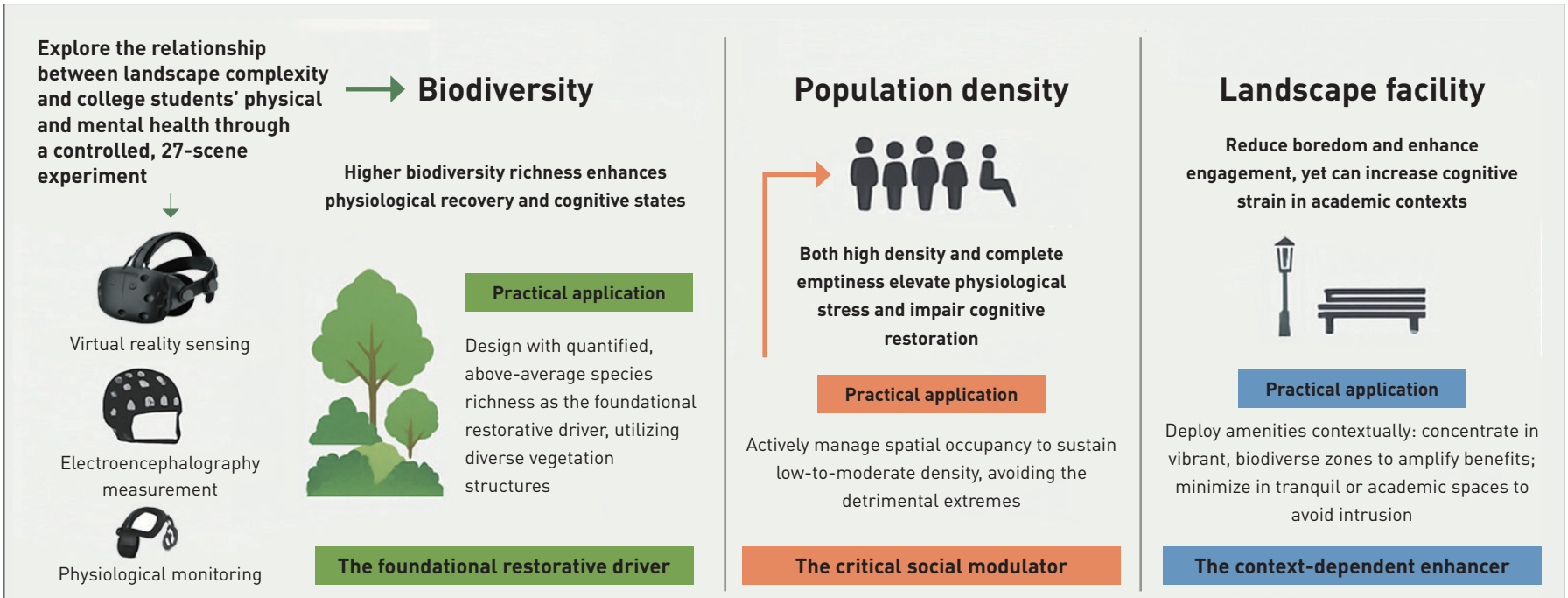
Impact of the Landscape Complexity of Campus Green Spaces on Students' Health Using Virtual Reality Models and EEG Analysis

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GRAPHICAL ABSTRACT



ABSTRACT

Campus green spaces are critical restorative areas specifically for students, who are under high levels of pressure, and a hotspot topic of increasing interest is how to create a healthy campus environment. However, the extent to which campus green elements affect students' restorative potential needs to be studied in more depth. This study examined the effects of landscape complexity—in terms of biodiversity, population density, and landscape facility—on college students' physical and mental health through controlled experiments by combining virtual reality technology, electroencephalography, and other physiological measurement

techniques. Analyses revealed that higher biodiversity predicted lower physiological stress and enhanced positive cognitive states. Population density predominantly exhibited negative effects, elevating systolic blood pressure and cognitive stress. The impact of landscape facilities was contingent on social context, alleviating boredom in crowded settings but showing diminished benefit in low-density areas. Critically, interaction analysis identified an optimal configuration for cognitive restoration: high biodiversity, minimal population, and modest facilities. The findings challenge simplistic design heuristics, arguing instead for a synergistic approach where ecological richness forms the essential foundation, social density is carefully curated, and built amenities are strategically deployed as contextual enhancers. This refines theoretical models of restorative environments by specifying the operative mechanisms within academic settings and provides a nuanced, evidence-based blueprint for creating cognitively supportive campus ecosystems.

KEYWORDS

Environmental Perception; Restorative Environments; Landscape Complexity; Campus Green Space; Physical and Mental Health; Electroencephalography; Virtual Reality

HIGHLIGHTS

- Biodiversity consistently aids restoration by reducing physiological stress and enhancing cognitive engagement
- Population density impairs recovery nonlinearly, where both overcrowding and emptiness yield suboptimal outcomes
- Landscape facilities act as contextual modulators, dependent on existing biodiversity and social density
- High biodiversity with low density, refined by strategic facilities, can achieve optimal restoration
- This study advances a multidimensional, mechanism-explicit framework for evidence-based environmental design

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1 Introduction

The escalation of urbanization and the resultant growth in urban populations have accelerated the pace of life and intensified social competition, contributing to heightened stress levels. Such stress is increasingly recognized as a precursor to mental health issues, especially depression and anxiety[1–2]. Globally, as substantiated by WHO[3], statistics indicate a notable 5%–6% annual incidence rate of depression among adults, with a discernible upward trajectory evident over successive years. In 1983, Stephen Kaplan introduced the notion of "restorative environments," defining them as spaces aiding recovery from mental fatigue and alleviating the negative emotional impact of stress[4]. Underpinned by Kaplan and counterparts, the sphere of research pertaining to the health impacts of restorative environments is swiftly evolving, exploring new avenues beyond conventional medical means to address public health concerns[5–6]. Numerous empirical studies have proved that the potential for restorative environment interventions to serve as viable avenues for improving mental health[7–11].

The physical attributes of green spaces play a pivotal role in their restorative capacity. Among these, visual characteristics stand as crucial determinants shaping the restorative potential of a landscape that encompasses several aspects such as complexity, naturalness, coherence, and historicity[12]. As pointed out by Åsa Ode, landscape complexity serves as a sound indicator in describing visual features, encapsulating the diverse shapes, textures, colors, and dimensional aspects present in flowers, foliage, topography, structures, and materiality[13]. Considering that it encompasses ecological diversity and the array of landscape amenities, some scholars posit that human presence and degree of crowding also significantly mold this complexity[14–15].

The notion of "landscape complexity" serves as a potential linkage between design and environmental psychology[16–17], commonly used by landscape professionals in evaluative studies[15,18–19]. Existing studies have revealed the close nexus between environmental biodiversity and human well-being[20–23]. For instance, studies have highlighted the correlation between population density in urban natural environments and individuals' physical and mental well-being, indicating that higher-density locales are associated with heightened negative emotions and psychological stress[24–26]. Åsa Ode and David Miller's investigation on landscape element richness favored landscapes characterized by moderate element distribution over those with many uniform elements[15]. Similarly, Yongli Fang's work found positive associations between landscape elements and public health[27], and

Li Deng's research showcased their varying degrees of impact on human health and recovery[28].

Prior investigations exploring landscape complexity and its impact on restorative environments have primarily centered on natural settings such as wilderness areas, forests, and coastal regions[4,6,21,29]. However, recent strides have begun examining the restorative attributes of densely populated urban settings with varying levels of complexity[30–31]. Dmitri Karmanov et al.'s study highlighted that urban spaces characterized by diverse species, thoughtful design, whilst aesthetically pleasing, hold the capacity to alleviate stress and uplift emotional well-being[32]. Shaohua Tan's interviews with urban dwellers unveiled that parks boasting a multitude of landscape elements and ample public amenities emerged as preferred sites for daily stress relief[33]. Moreover, numerous studies conducted in healthcare settings such as hospitals and nursing homes have consistently demonstrated the positive impact of lush greenery with rich planting and thoughtful landscaping on the physical and mental health of patients and residents[34–36]. From natural settings to urban and healthcare environments, as a crucial descriptor to the configuration of landscape elements, landscape complexity has been extensively validated across various types of green spaces. Its application to campus green spaces, however, remains an underexplored domain and these spaces are increasingly under scholarly scrutiny as potential restorative environments within high-density urban contexts[37–39].

Overall, existing studies have highlighted campus green spaces as potentially restorative environments, capable of alleviating mental fatigue, stress, and aiding in concentration restoration for students[40–44]. Building upon this notion of landscape complexity, its investigation within campus settings has followed two predominant paths. One research strand examines the relationship between macro-scale compositional metrics of campus green spaces (e.g., greening ratios, spatial layout) and broad well-being outcomes[37–38,40,44]. Another, aligned with the "healing campus," focuses on the effects of specific, discrete interventions (e.g., horticultural therapy gardens) or aggregates self-reported restorative experiences[21,38–39,45]. While these approaches affirm the value of complex campus landscapes, they offer limited insight into the fine-grained, psychophysiological mechanisms through which the configurational aspects of this complexity—the specific interplay of ecological, social, and built elements encountered by students—produce immediate restorative effects. Their restorative potential is embedded in this very complexity of lived experience, necessitating an exploration rooted in landscape complexity to elucidate the nexus between campus landscapes and students[37–40]. Moreover, akin to other demographics, college students confront multifaceted stressors—social, academic, and environmental—which without adequate psychological recovery, might predispose them to depression and mental health disorders, particularly during pivotal life stages[46–48]. A macro-scale lens lacks the resolution to dissect these experiential intricacies, while a focus on singular elements or retrospective reports may not capture the interactive and context-dependent psychological dynamics that characterize real-time restoration in such multi-faceted settings.

The limitations above converge to define a specific gap: a need to deconstruct the overarching concept of campus landscape complexity into a measurable framework that can explain its configurational impact on restoration. First, while complexity is recognized as vital, its application to campus environments lacks a dedicated operational framework that translates the concept into specific, context-grounded dimensions reflective of the campus' unique socio-ecological fabrics. Second, key factors acknowledged to constitute this complexity—such as "biodiversity"[21,40,49], "population density"[50–51], and "landscape facility"[9,27–28]—have typically been examined in isolation, leaving their combined, interactive effects largely unexplored. Third, methodological reliance on psychological scales has precluded synergistic physiological–psychological monitoring, limiting insight into the embodied mechanisms of recovery. To bridge this gap, a focused conceptualization is required. The campus environment is fundamentally defined by the interplay of managed ecology, high-density social dynamics, and programmed infrastructure[39]. Consequently, the restorative quality of its landscapes can be understood as most directly governed by the configurational interplay of three constitutive and designable dimensions: ecological richness (biodiversity), social density (population density), and functional provision (landscape facilities)[37–41]. These dimensions are prioritized as they represent the primary, modifiable attributes from which campus landscape complexity arises. Other perceptual qualities (e.g., openness, legibility) are best understood as secondary, emergent properties contingent upon this core triad. Investigating these interactions necessitates methods capable of simultaneous multi-factor manipulation and multi-modal, objective measurement.

To address these gaps, this study employed controlled virtual reality (VR) experiments coupled with multimodal physiological and neural monitoring to systematically explore the impact of the landscape complexity of campus green spaces on students' restorative outcomes. The overarching aim is to elucidate how

the multifaceted construct of landscape complexity, through the aforementioned framework of biodiversity, population density, and landscape facilities that jointly influences the psycho-physiological restoration process in a campus context with two sequential analytical objectives: 1) to quantify the individual associations of each complexity dimension with a spectrum of restorative indicators, encompassing physiological arousal, self-reported emotion, and EEG-derived cognitive-affective states; and 2) to decipher the patterns of interaction among these three dimensions, testing the proposition that their combined configurations exert effects on restorative outcomes that are not fully predictable from their individual contributions.

2 Materials and Methods

2.1 Participants

Prior to the experiment, an a priori power analysis was performed using a repeated-measures ANOVA model with within-between interaction, with a medium effect size (f = 0.25), an alpha level of 0.05, and a statistical power of 0.95. The calculation determined that this study required a minimum of 30 participants.

This study recruited student participants from Southwest University of Science and Technology, China, through an announcement posted on the university's webpage. Eligible participants must meet specific criteria: aged between 18 and 28 years, in good health without chronic conditions, non-smokers, not currently using medications, and maintaining adequate sleep. Moreover, participants should not have experienced any muscular discomfort during the VR experience.

Prior to the formal experiment, all eligible participants underwent a brief VR familiarization and tolerance test, which involved wearing the headset and experiencing a neutral virtual environment for several minutes. Individuals who reported any strong discomfort during this screening phase were not proceeded to the main experiment. Initially, 74 individuals met the inclusion criteria. However, during the experiment, six participants encountered disrupted EEG device connections due to significant movement, leading to discontinuous data. Hence, the full set of experiments and assessments was completed by 68 participants, comprising 32 males and 36 females, with an average age of 22.48 ± 2.15 yr.

A sensitivity analysis with the final sample of 68 participants verified the capability to detect subtle effects. The results demonstrate that the study design possesses adequate statistical power (95%) to detect effect sizes of $f \geq 0.154$, confirming the statistical robustness of the sample size, ensuring the reliability of the research findings.

2.2 VR Modeling

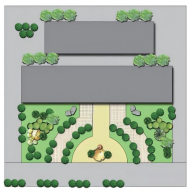
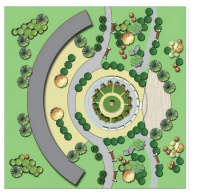
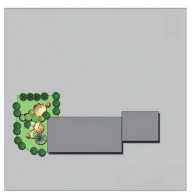
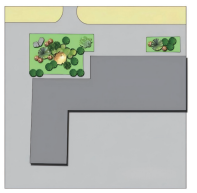
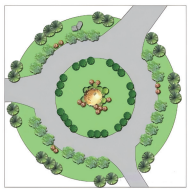
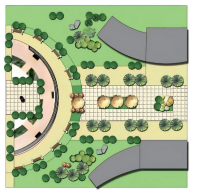
Preceding the experiment, we utilized SketchUp to model the scene, employed Enscape for rendering, and generated an executable file serving as the experimental sample, which was played during the recovery phase of the experiment. Participants used HTC's Vive VR headset to engage with these scenes. The impact of virtual natural settings on participants manifests in positive physiological and psychological effects[52], supported by research indicating parallels to real natural environments[53–55].

2.3 Design and Procedure

Prior to the formal experiment, the effectiveness of the scenes in eliciting genuine physiological responses was validated in a pilot study (N = 15). Participants rated the environments highly on measures of perceived realism and immersion. More crucially, the time-performance analysis of physiological data provided objective evidence: a significant reduction in stress markers—e.g., heart rate (HR), blood pressure (BP)—was observed within the first 3–5 min of VR exposure. This specific trajectory—rapid initial improvement tapering to a steady state, with some indicators showing a slight rebound in the final 5–10 min. This strongly suggests that our virtual environments were not merely visual representations but potent enough to trigger genuine restorative processes in participants. Cognizant on the importance of a coherent VR model, 10 major landscape nodes across the campus were identified and classified, encompassing varied functional types of green spaces (Table 1): plazas adjacent to teaching building, student dormitory green spaces, roadside greenways, and entrance square. The teaching building atrium was selected as the base model precisely because this category emerged from our pre-site study as a highly frequented, high-stress, and thus critically important typology for restorative intervention.

In the VR scenes, three landscape complexity indices, namely, biodiversity, population density, and landscape facility, were expanded by increasing their respective numbers and types to portray three levels of campus landscapes, ranging from low to high complexity. Biodiversity denotes the variety of plant species, population density signifies the number of individuals within the scene, and landscape facility encapsulates the assortment and quantity of installed amenities. By arranging and combining these indices across three levels, 27 distinct scenes were generated (Fig. 1). For grading complexity factors into Levels I (high), II

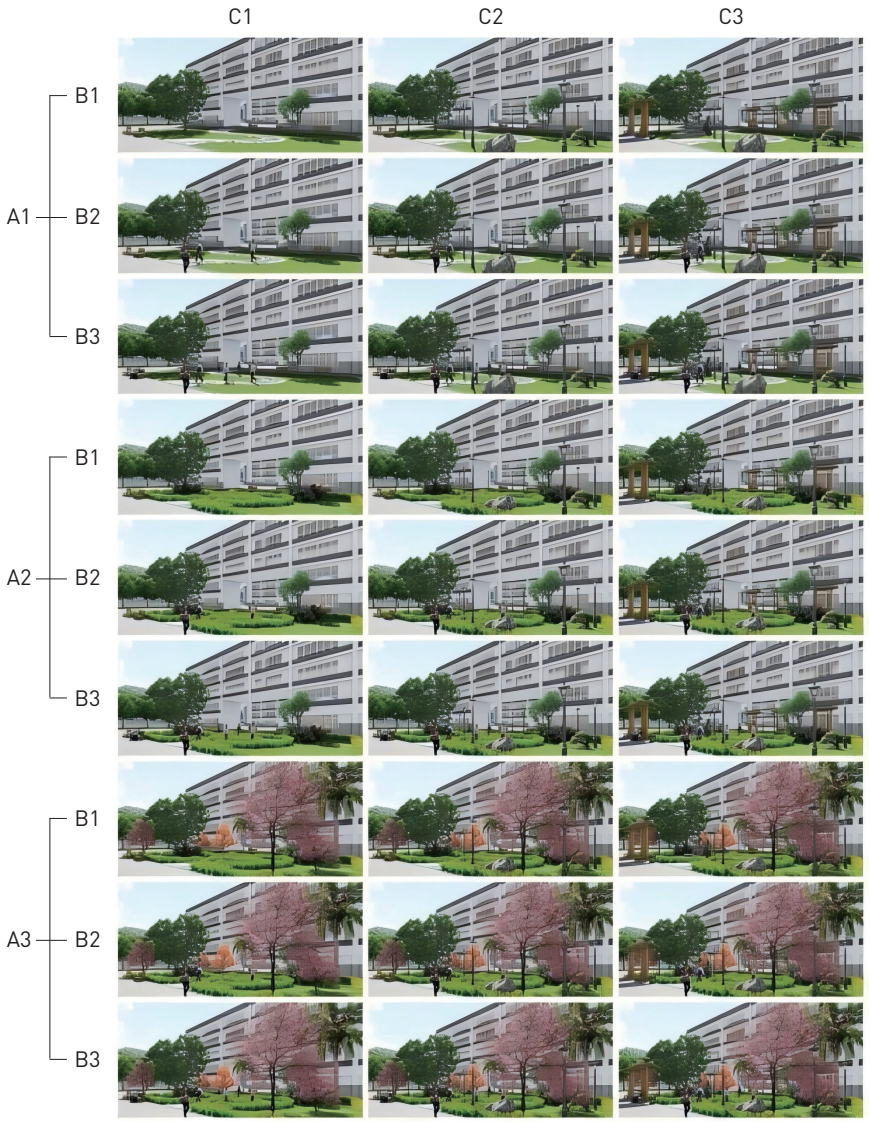
Table 1: Site plans of the selected landscape nodes

Node name	Green space type	Site plan	Node name	Green space type	Site plan
Node A: the plaza in front of the Materials Science Building	Green space adjacent to teaching building		Node F: the green space in front of the Administration Building	Green space adjacent to teaching building	
Node B: the green space in front of Qinghua Building	Green space adjacent to teaching building		Node G: the square of Technology Light	Green space adjacent to teaching building	
Node C: Liu Pond	Greenway adjacent to waterbody		Node H: the Yinxing Road Square	Roadside greenway	
Node D: the green space in front of Building 1, Beiyuan	Green space adjacent to student dormitory		Node I: the green space in front of the Administration Building	Green space adjacent to teaching building	
Node E: the roundabout green space on Longshan Road	Roadside greenway		Node J: Square of Technology Light	Entrance square green space	

(medium), and III (low), a comprehensive audit was conducted across the selected landscape nodes to establish reference mean values for each complexity tier.

It should be noted that the resulting levels, e.g., "high population" as 7 individuals, represent relative designations within the experimental framework, where the number 7 signifies a "high" level relative to the "medium" (4) and "low" (0) conditions in this study, operationalized to model a perceptible state of crowding. It does not represent an absolute threshold for high density in all real-world campus contexts but serves as a controlled variable to investigate the effects of relative social density variations. The criteria for the three experimental levels of each primary manipulated variable were defined in supplementary materials.

To begin, participants were informed of the procedure and provided their identity information before the test. Then they were given 5 min to familiarize themselves to the equipment, aided by a lab technician. Throughout the procedure, EEG data was continually recorded while baseline physiological measurements were taken during a 3-minute resting period. Following this, participants engaged in a stress-inducing task—a 3-minute English listening exercise—during which physiological measurements were collected. Post stress administration, BP measurements were taken, and participants completed the State Anxiety Inventory (S-AI) scale to measure their emotional and physical stress levels. Each of the 27 VR



Biodiversity: A1 < A2 < A3; **population density:** B1 < B2 < B3; **landscape facility:** C1 < C2 < C3

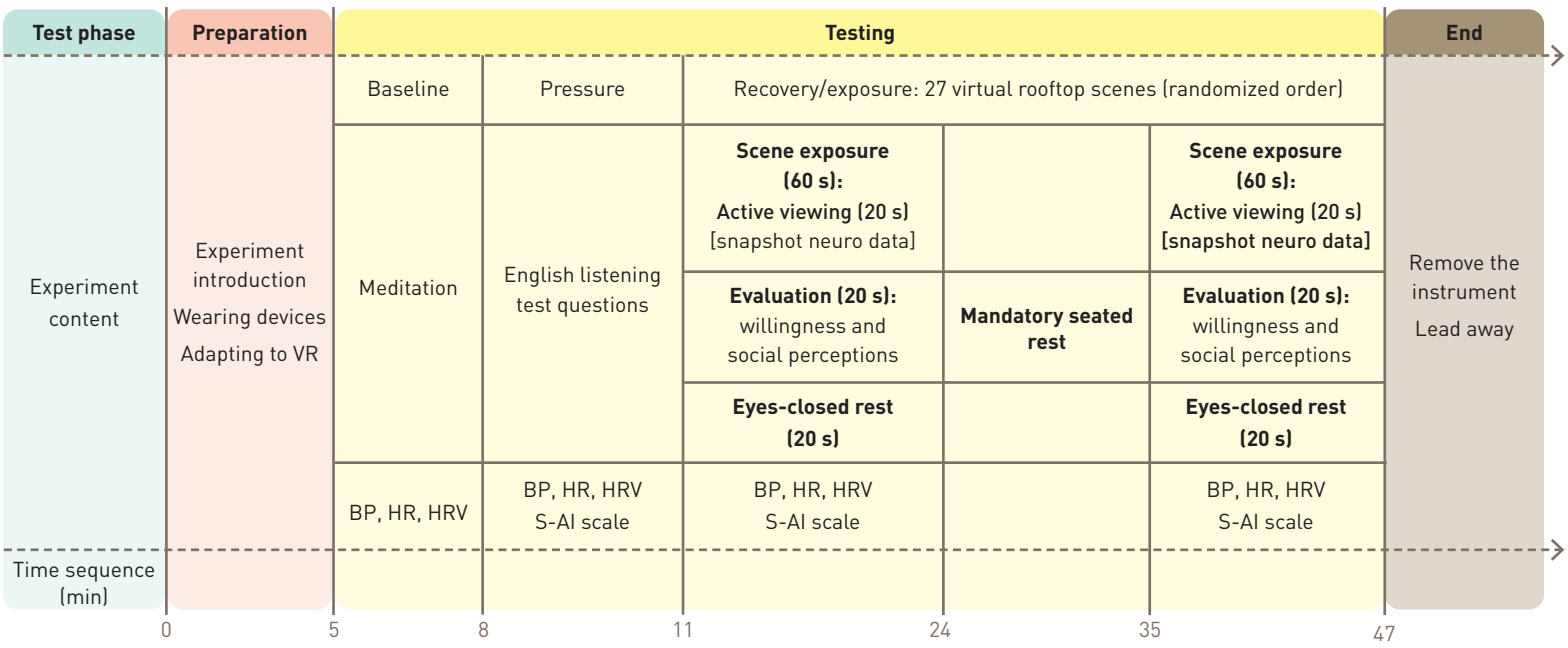
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scenes was presented for a duration of 1 min in a fully randomized order. This exposure time was selected based on empirical studies demonstrating that short-term visual immersion in natural or restorative virtual environments can elicit significant initial shifts in autonomic nervous system activity, e.g., heart rate variability (HRV), and self-reported affective state within the first few minutes[29,55–57]. Our primary aim was to assess the initial restorative potential and the efficiency of different landscape complexes in triggering the early phase of recovery from acute stress, rather than to map the complete trajectory to full physiological baseline stabilization. After exposing to each VR scene, participants completed the S-AI again, and physiological data were recorded. The entire experiment encompassed a single trial lasting approximately 47 min (Fig. 2).

2.4 Instruments

2.4.1 Psychological Indicators

To assess psychological indicators obtained from the procedure, the research utilized the abbreviated version of the S-AI scale, which distilled the core affective dimensions from the full scale. This adaptation was employed to mitigate participant fatigue during the intensive repeated-measures protocol, while preserving the measurement of key transient psychological states. The abbreviated scale comprised six psychological dimensions: relaxation, contentment, calmness, nervousness, disturbance, and annoyed. Participants rated these items on a 4-point scale ranging from 1 (not at all), 2 (somewhat), 3 (moderately) to 4 (very pronounced). Rigorous testing and comprehensive validation confirmed the



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Fig. 1 The VR scenes of varying complexity used in the experiment.
Fig. 2 Experiment procedure.

effectiveness of this abbreviated S-AI scale[52], demonstrating its comparative efficacy to the full-scale version.

2.4.2 Physiological Signals

Physiological signals were tracked utilizing the Didoy2 medical-grade BP monitoring bracelet. The monitored physiological parameters encompassed HR, HRV, and BP, encompassing both diastolic BP (DBP) and systolic BP (SBP) measurements.

2.4.3 Cognitive Signals

Cognitive signals were captured through the Emotiv Epoc portable EEG device. Emotiv Pro, the associated software, translates raw EEG data (electrode positions) into 10 different cognitive states, including boredom, attention, visual attention, excitement, engagement, interest, focus, cognitive stress, relaxation, and stress. These 10 cognitive-affective metrics are derived by the software's proprietary algorithms, which analyze patterns in the raw EEG signal across standard frequency bands (e.g., α, β, θ, γ). The algorithms are trained to associate specific combinations of spectral power and spatial patterns with psychological states. For instance, states like engagement and focus are typically associated with decreased α power (8–13 Hz) and increased β power (13–30 Hz) in frontal and parietal regions, indicative of heightened cognitive processing. Conversely, states like relaxation are often linked to increased α power; stress and cognitive stress metrics may reflect patterns of increased high-β or -γ activity coupled with decreased α. The precise algorithmic weights and models are proprietary; in this research, the interpretation focuses on the relative changes and patterns across experimental conditions rather than absolute values (Table 2). These specific cognitive states served as metrics to understand the potential restorative impact of the campus green spaces.

Table 2: Descriptions of EEG-derived cognitive state metrics

Metric	Conceptual description
Boredom	A state of low arousal and lack of interest in the current environment or task
Attention	The general cognitive process of concentrating mental resources on stimuli or tasks
Visual attention	Attention specifically directed toward visual stimuli and processing
Excitement	A state of high arousal and positive anticipation
Engagement	The degree of cognitive involvement and investment in an activity or environment
Interest	A cognitive and affective state of curiosity and positive engagement with specific content
Focus	Sustained, concentrated attention on a specific target, filtering out distractions
Cognitive stress	Mental strain or overload arising from demanding cognitive processing
Relaxation	A state of low physiological arousal and calmness, free from tension
Stress	A broader state of physiological and psychological arousal in response to perceived challenge or threat

2.5 Analyses

A one-way repeated measures analysis of variance (ANOVA) was applied to discern the potential effects attributed to the varying degrees of landscape complexity on the variables. Correlation analyses were conducted to explore the relationship between psychological indicators, physiological signals, and cognitive signals with the landscape complexity factors. Notably, each signal demonstrated significant correlations with the complexity factor.

Multiple linear regression was employed to explore the relationship between the landscape complexity of campus green spaces and participants' physical and mental well-being. Here, biodiversity, population density, and landscape facility served as independent variables, while psychological, physiological, and cognitive metrics acted as dependent variables. For the quantification of each index, a virtual coding approach was adopted based on prior research[58–60]. The value assigning is shown in Table 3. All statistical analyses were conducted using IBM Statistics SPSS version 26.

Table 3: Value assigning of independent variables

Assigned value	1	2	3
Biodiversity	Low biodiversity	Medium biodiversity	Complex biodiversity
Population density	Little population	Small population density	Large population density
Landscape facility	None	A small amount of landscape facilities	A large amount of landscape facilities

Additionally, Spearman's rank correlation coefficient was employed to examine potential associations among all study variables, with significance set at $p < 0.05$.

3 Results

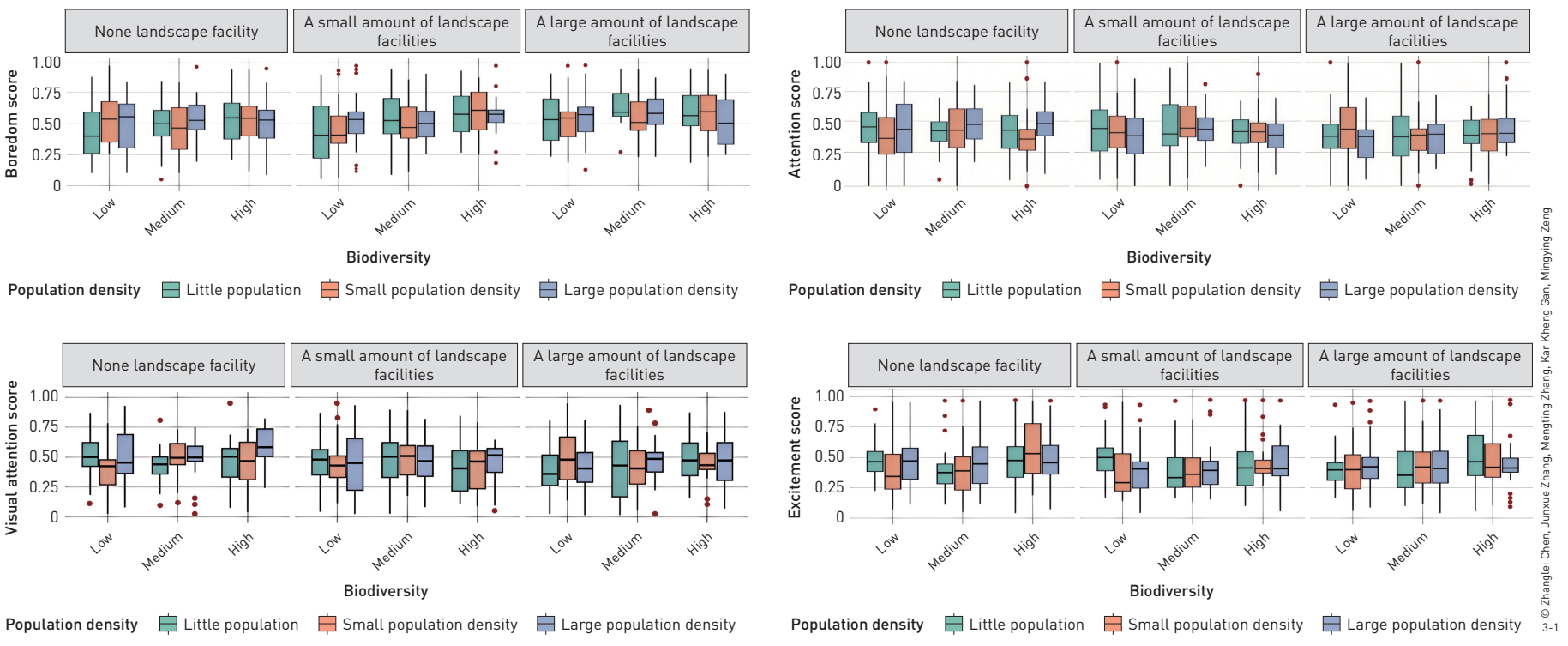
3.1 Descriptive Statistical Analyses of Physiological, Cognitive, and Psychological Signals Among Landscape Complexity Factors

Descriptive statistical analyses were conducted using boxplots to elucidate the impact patterns of the landscape complexity of campus green spaces on various health dimensions. Overall, all indicators consistently demonstrated that the configuration of high biodiversity with little population yielded the most pronounced positive effects—the median of positive cognitive indicators (e.g., interest, focus) increased to above 0.75, while the median of physiological indicators (e.g., *HR*) decreased to below 75 bpm. Conversely, the combination of low biodiversity with large population exhibited the strongest negative effects, with the median of negative cognitive indicators (e.g., stress) rising above 0.75, and *HR* and *SBP* exceeding 85 bpm and 125 mmHg, respectively. Data dispersion markedly increased under intermediate environmental conditions (interquartile range expanded by approximately 40%–60%), reflecting significant individual response variability.

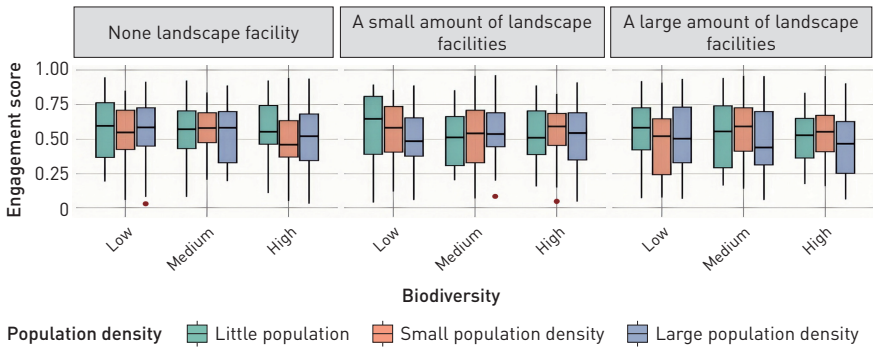
Among the three indicator types, cognitive signals exhibited the highest sensitivity to gradients in landscape complexity, whereas psychological and physiological indicators showed comparatively limited responsiveness. This discrepancy primarily stems from two reasons: first, physiological signals such as HRV are strongly influenced by individual basal metabolic characteristics (inter-individual differences account for over 70% of variance), resulting in highly dispersed distributions across all conditions (box lengths 2–3 times those of other indicators), which obscures environmental effects. Second, psychological indicators are constrained by the sensitivity limits of self-report scales. For instance, nervousness scores were confined to a narrow score range of 1.31–1.59 across scenes, indicating a notable floor effect. Consequently, subsequent analyses focused on cognitive indicators, which provide a more precise measure of environmental intervention responses (Fig. 3).

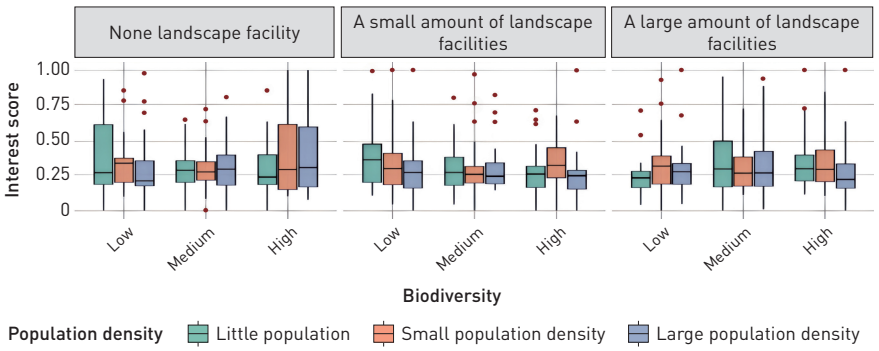
Cognitive signals displayed clear environmental gradient effects: positive cognitive metrics such as attention (0.20→0.60), visual attention (0.25→0.75), engagement (0.25→0.75), interest (0.25→0.75), focus (0.25→0.75), and relaxation (0.25→0.75) showed improvements exceeding 200% under optimal conditions. In contrast, negative state indicators like boredom (0.75→0.40), excitement (0.75→0.25), cognitive stress (0.75→0.30), and stress (0.75→0.30) were reduced by approximately 48%–60% under optimal conditions (Fig. 3).

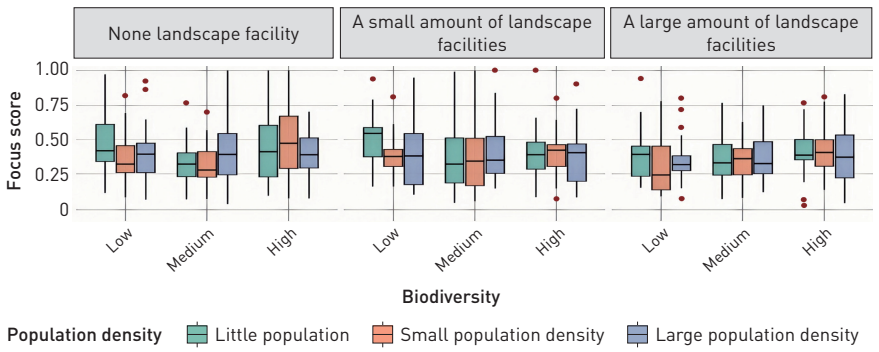
Fig. 3 The distribution of the score of each cognitive state among landscape complexity factors.

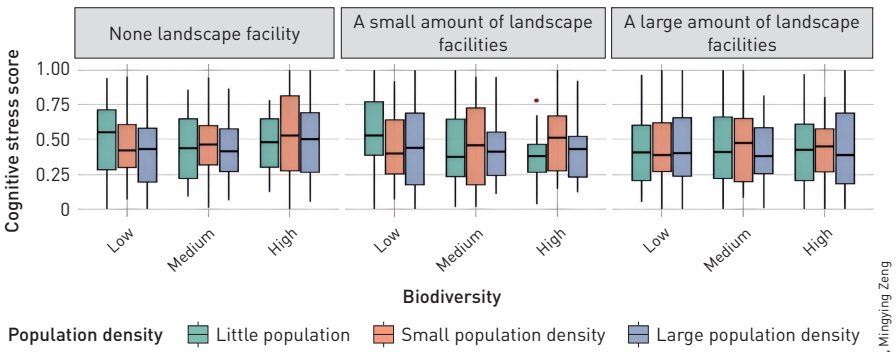


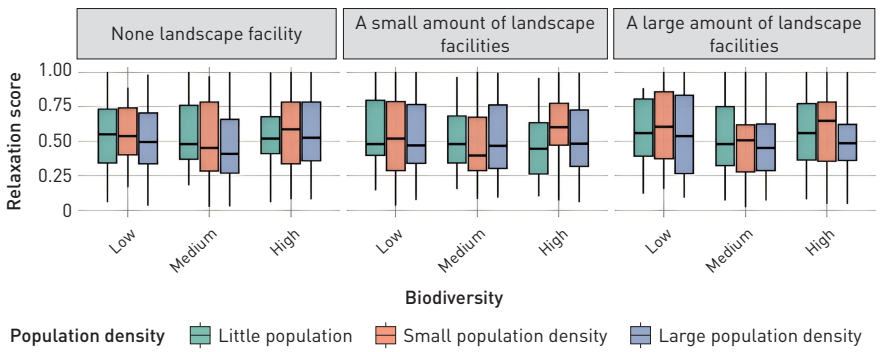
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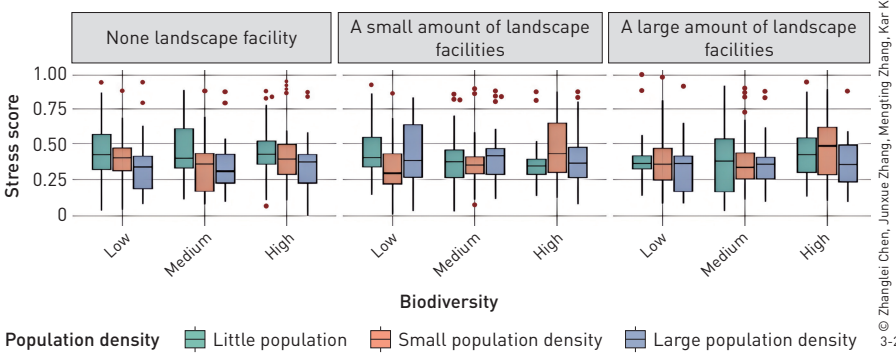












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3.2 Correlation Analyses Between Biodiversity and Physiological, Psychological, and Cognitive Indicators

As shown in Table 4, the outcomes of the multiple linear regression analyses revealed that alterations in biodiversity exhibited a positive impact on feelings of relaxation and contentment, while showcasing negative influences on cognitive states related to calmness, nervousness, and disturbance. The effects of biodiversity on psychological indicators were notably significant, where an increment of biodiversity by one led directly to enhanced feelings of relaxation ($F = 20.398$, $p = 0.00$) and contentment ($F = 9.928$, $p = 0.004$) by 0.080 and 0.090, respectively. Besides, it triggered declines in calmness ($F = 7.183$, $p = 0.013$), nervousness ($F = 21.854$, $p = 0.00$), and disturbance ($F = 4.833$, $p = 0.037$) by 0.098, 0.064, and 0.060, respectively.

Furthermore, multiple linear regression analyses also showed that population density had a significantly positive effect on *HR*, *DBP*, and *SBP*. An increase in population density by one corresponded directly to *HR* ($F = 4.859$, $p = 0.037$) rising by 0.627, *DBP* ($F = 4.333$, $p = 0.048$) by 0.884, and *SBP* ($F = 4.497$, $p = 0.044$) by 1.161. However, there was not a considerable effect of population density on *HRV* ($F = 0.715$, $p = 0.406$).

Moreover, the multiple linear regression analyses demonstrated that biodiversity notably impacted cognitive stress, interest, relaxation positively, and boredom negatively. An incremental rise of one in biodiversity directly led to an increase in cognitive stress ($F = 5.279$, $p = 0.030$) by 0.011, interest ($F = 12.440$, $p = 0.002$) by 0.016, and relaxation ($F = 9.773$, $p = 0.004$) by 0.015, while eliciting a decrease in boredom ($F = 8.256$, $p = 0.008$) by 0.013. However, the impact of biodiversity on other six cognitive states was not found to be statistically significant.

Table 4: Regression analysis of biodiversity as independent variable

Dependent variable		Unstandardized coefficient		Standardized coefficient	*t*	*Sig.*
		β	Standard error	β		
Psychological	Relaxation (+)	0.080*	0.014	0.670	5.593	0
	Contentment (+)	0.090*	0.025	0.533	3.556	0.004
	Calmness (+)	−0.098*	0.034	−0.472	−2.914	0.013
	Nervousness (−)	−0.064*	0.012	−0.706	−5.482	0
	Disturbance (−)	−0.060*	0.025	−0.403	−2.364	0.037
	Annoyed (−)	0.005	0.018	0.054	0.295	0.788
Physiological	HRV (+)	−0.407	0.558	−0.148	−0.730	0.461
	HR (−)	−0.826**	0.238	−0.531	−3.470	0.004
	DBP (−)	−0.976*	0.391	−0.424	−2.498	0.027
	SBP (−)	−1.140*	0.456	0.383	−2.501	0.048
Cognitive	Boredom (−)	−0.013**	0.004	−0.498	−3.203	0.008
	Attention (+)	0.002	0.003	0.158	0.908	0.432
	Visual attention (+)	−0.007	0.004	−0.295	−1.697	0.135
	Excitement (+)	0.002	0.004	0.127	1.056	0.053
	Engagement (+)	−0.003	0.003	−0.170	−1.078	0.398
	Interest (+)	0.016**	0.004	0.576	4.477	0.002
	Focus (+)	0.005	0.004	0.002	0.012	0.990
	Cognitive stress (+)	0.011**	0.004	0.418	2.451	0.003
	Relaxation (+)	0.015**	0.005	0.530	3.035	0.004
	Stress (−)	−0.002	0.007	−0.369	−1.392	0.732

NOTES

1. * indicates the significance level is less than 0.05 and ** denotes significance level less than 0.01.
2. (+) indicates a factor that positively affects physical and mental well-being and (−) indicates a factor that negatively affects physical and mental well-being.

3.3 Correlation Analyses Between Population Density and Physiological, Psychological, and Cognitive Indicators

As indicated in Table 5, the multiple linear regression analyses revealed that population density exerted a significant and positive influence on feelings of relaxation and contentment, while demonstrating a significant and negative impact on calmness and nervousness. An increment in population density by one directly led to diminished relaxation (F = 4.963, p = 0.035) and contentment (F = 4.297, p = 0.049) by 0.049 and 0.064, respectively. Yet, it triggered an elevation in calmness (F = 5.202,

Table 5: Regression analysis of population density as independent variable

Dependent variable		Unstandardized coefficient		Standardized coefficient	*t*	*Sig.*
		β	Standard error	β		
Psychological	Relaxation (+)	−0.049*	0.014	−0.407	−3.396	0.035
	Contentment (+)	−0.064*	0.031	−0.383	−2.073	0.049
	Calmness (+)	−0.086*	0.034	−0.415	−2.560	0.031
	Nervousness (−)	0.031*	0.012	0.341	2.642	0.045
	Disturbance (−)	0.006	0.030	0.042	0.212	0.834
	Annoyance (−)	0.026	0.018	0.266	1.446	0.180
Physiological	HRV (+)	0.458	0.558	0.167	0.822	0.406
	HR (−)	0.627*	0.238	0.403	2.634	0.015
	DBP (−)	0.884*	0.391	0.384	2.263	0.033
	SBP (−)	1.161*	0.456	0.390	2.548	0.018
Cognitive	Boredom (−)	−0.005**	0.004	−0.198	−1.274	0.002
	Attention (+)	0.004	0.003	0.264	1.368	0.184
	Visual attention (+)	−0.009	0.004	−0.173	−0.998	0.387
	Excitement (+)	0.005	0.004	0.160	1.335	0.425
	Engagement (+)	−0.009**	0.003	−0.548	−3.280	0.003
	Interest (+)	0.013	0.004	0.461	3.583	0.065
	Focus (+)	−0.005	0.004	−0.242	−1.227	0.223
	Cognitive stress (+)	0.250*	0.004	0.399	2.358	0.027
	Relaxation (+)	0.002	0.006	0.061	0.304	0.764
	Stress (+)	0.017**	0.006	0.517	2.935	0.006

NOTES

1. * indicates the significance level is less than 0.05 and ** denotes significance level less than 0.01.
2. (+) indicates a factor that positively affects physical and mental well-being and (−) indicates a factor that negatively affects physical and mental well-being.

p = 0.031) and decrease of nervousness (F = 4.434, p = 0.045) by 0.086 and 0.031. However, in this experimental context, population density exhibited no notable effect on disturbance (F = 0.045, p = 0.834) or annoyance (F = 1.903, p = 0.180).

In addition, the multiple linear regression analyses unveiled that population density significantly and positively impacted *HR*, *SDP*, and *DBP*. A one-unit increase in population density resulted in a direct increase of 0.627 in *HR* (F = 4.859, p = 0.037), 0.884 in *DBP* (F = 4.333, p = 0.048), and 1.161 in *SBP* (F = 4.497, p = 0.044). However, population density did not exhibit a substantial effect on

HRV (F = 0.715, p = 0.406).

Lastly, through the multiple linear regression analyses, it was observed that population density significantly and positively affected cognitive stress and stress while displaying a significant negative impact on boredom and engagement. An increase in population density by one resulted in a decrease in boredom (F = 4.023, p = 0.022) and engagement (F = 10.757, p = 0.003) by 0.025 and 0.009, respectively. Meanwhile, cognitive stress (F = 3.279, p = 0.027) and stress (F = 9.132, p = 0.006) increased by 0.025 and 0.017, respectively. However, population density did not significantly affect other six cognitive states.

3.4 Correlation Analyses Between Landscape Facility and Physiological, Psychological, and Cognitive Indicators

In Table 6, the multiple linear regression analysis demonstrates that landscape facility had a significant positive impact on feelings of contentment and a significant negative impact on feelings of disturbance. An increase of one in landscape facility led directly to a rise of 0.064 in contentment (F = 4.434, p = 0.018); conversely, it resulted in a reduction of 0.061 in feelings of disturbance (F = 5.096, p = 0.033). However, in this experiment, landscape facility did not exhibit a significant effect on other four feelings.

Additionally, according to the multiple linear regression analyses, landscape facility had a significant negative impact on *SDP* (F = 4.777, p = 0.038), where an increase of one in landscape facility resulted directly in a 1.191 decrease in *SDP*. However, landscape facility did not demonstrate a significant effect on *HRV* (F = 0.071, p = 0.793), *HR* (F = 0.388, p = 0.539), or *DBP* (F = 0.214, p = 0.647).

Furthermore, the multiple linear regression analyses showcased that landscape facility significantly positively influenced cognitive stress and excitement while significantly negatively affecting boredom, attention, and visual attention. An incremental increase

Table 6: Multiple regression analysis of landscape facility as independent variable

Dependent variable		Unstandardized coefficient		Standardized coefficient	*t*	*Sig.*
		β	Standard error	β		
Psychological	Relaxation (+)	0.028	0.023	0.234	1.203	0.24
	Contentment (+)	0.064*	0.025	0.228	1.521	0.018
	Calmness (+)	−0.002	0.034	−0.008	−0.051	0.967
	Nervousness (−)	0.005	0.012	0.055	0.424	0.976
	Disturbance (−)	−0.061*	0.027	−0.412	−2.258	0.033
	Annoyed (−)	−0.038	0.018	−0.384	−2.089	0.068
Physiological	HRV (+)	0.146	0.558	0.053	0.261	0.793
	HR (−)	−0.192	0.309	0.124	0.623	0.539
	DBP (−)	−0.212	0.391	−0.092	−0.543	0.647
	SBP (−)	−1.191*	0.545	0.401	2.186	0.038
Cognitive	Boredom (−)	−0.011*	0.004	−0.395	−2.538	0.042
	Attention (−)	−0.007*	0.003	−0.459	−2.637	0.015
	Visual attention (−)	−0.011*	0.004	−0.434	−2.497	0.024
	Excitement (+)	0.010*	0.004	0.339	2.829	0.018

(Continued)

Table 6: Multiple regression analysis of landscape facility as independent variable (Continued)

Dependent variable		Unstandardized coefficient		Standardized coefficient	*t*	*Sig.*
		β	Standard error	β		
Cognitive	Engagement (+)	−0.005	0.003	−0.317	−2.016	0.107
	Interest (+)	0.008	0.004	0.271	2.107	0.171
	Focus (+)	−0.004	0.004	−0.206	−1.039	0.304
	Cognitive stress (+)	0.009*	0.004	0.385	2.258	0.047
	Relaxation (+)	0.003	0.005	0.116	0.665	0.564
	Stress (−)	0.004	0.006	0.116	0.659	0.564

NOTES

1. * indicates the significance level is less than 0.05 and ** denotes significance level less than 0.01.
2. (+) indicates a factor that positively affects physical and mental well-being and (−) indicates a factor that negatively affects physical and mental well-being.

of one in landscape facility directly led to a rise in cognitive stress (F = 4.345, p = 0.047) and excitement (F = 3.255, p = 0.018) by 0.009 and 0.010, respectively, while resulting in reductions in boredom (F = 4.616, p = 0.042), attention (F = 6.655, p = 0.015), and visual attention (F = 5.801, p = 0.024) by 0.011, 0.007, and 0.011, respectively. However, landscape facility did not significantly impact other five cognitive states.

3.5 Interactive Effects of Landscape Complexity Factors on Physiological, Psychological, and Cognitive Indicators

Interaction heatmaps were employed to visualize the interplay of the three landscape complexity factors. To delineate the core mechanisms with clarity and depth, the analysis focused on key outcome variables that demonstrated consistent and high sensitivity to variations in all three factors. Based on the regression analyses, boredom, cognitive stress, and *SBP* were identified as such pivotal variables, as they attained statistical significance across all regression models for the three independent factors. Consequently, through heatmap visualization, the most robust and central evidence chain was revealed, reflecting the impact of landscape complexity on physiological, psychological, and cognitive dimensions of health (Figs. 4–6).

As illustrated in Fig. 4, building upon the core finding that enhanced biodiversity and landscape facility effectively alleviate boredom while controlled population density is crucial, the heatmap analysis further revealed intricate nonlinear interaction

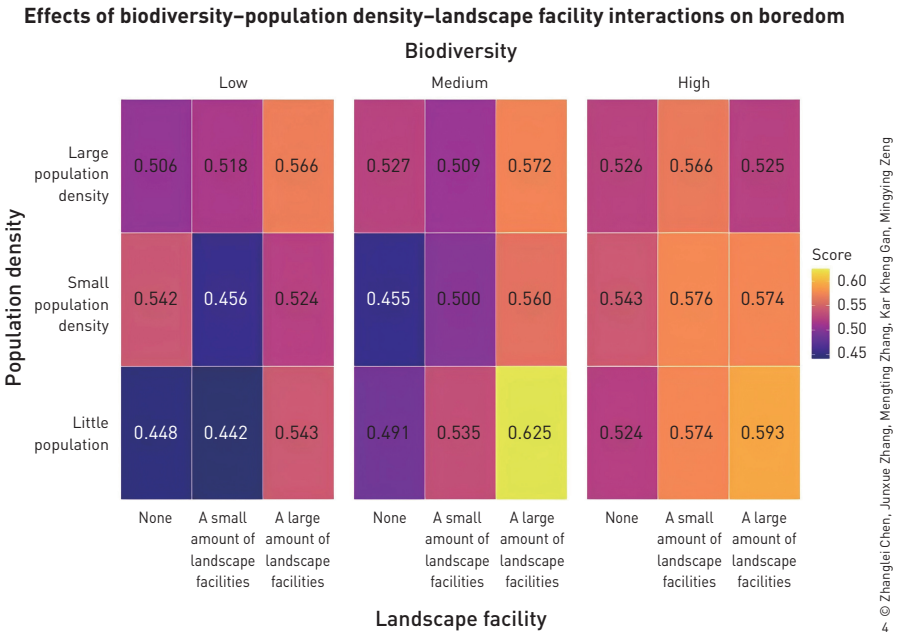


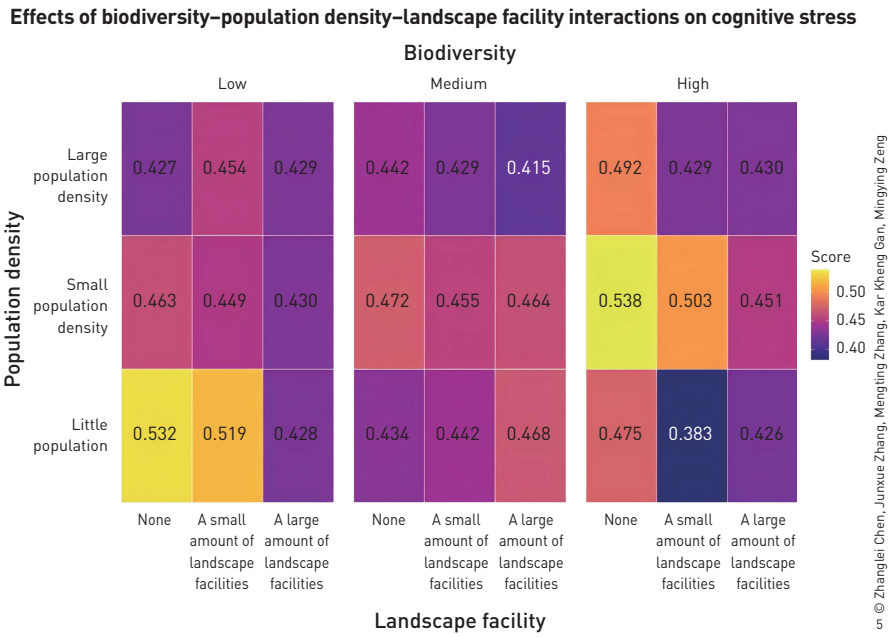
Fig. 4 The heatmap of the interaction effects of environmental indicators on boredom.

mechanisms among these factors. Biodiversity emerged as the most stable positive factor, significantly reducing boredom levels. However, the benefit of landscape facility exhibited a pronounced context-dependent effect: in high population density areas, its impact followed a "dose-threshold" pattern—an initial increase from none- to low-facility level paradoxically exacerbated negative affect (e.g., boredom increased from 0.526 to 0.566), with significant positive benefits only manifesting at the larger facility

level (boredom decreased to 0.525). Conversely, in low population density tranquil environments, the introduction of landscape facilities generally produced disruptive effects.

Figure 5 demonstrates that, while confirming the conclusion that increased biodiversity is key to mitigating cognitive stress and elevated population density exacerbates it, the heatmap unveiled a more nuanced and sophisticated pattern. It precisely identified the optimal configuration for minimizing cognitive stress (0.383) as high biodiversity–little population–small amount of landscape facility. This finding is critical, as it challenges the simplistic assumption that "the more natural and pure the environment, the better." It indicates that within an already near-optimal serene natural setting, introducing a small amount of carefully designed landscape facilities can provide a subtle, positive cognitive stimulus, thereby achieving the best restorative outcome.

Figure 6 confirms that the positive influence of biodiversity on physiological health and the significant negative effect of population density. Across all environmental configurations, high population density consistently resulted in elevated *SBP*, representing the most uniform and strong signal within the heatmap. For *SBP*, the heatmap clearly identifies high population density as the foremost environmental risk factor for increased *BP*. Furthermore, the research clarifies the mechanism of landscape facility: its beneficial effect on reducing *SBP* is distinctly context-dependent, becoming significant only in high-density areas characterized by rich biodiversity (e.g., *SBP* was reduced by approximately 1.7 mmHg).



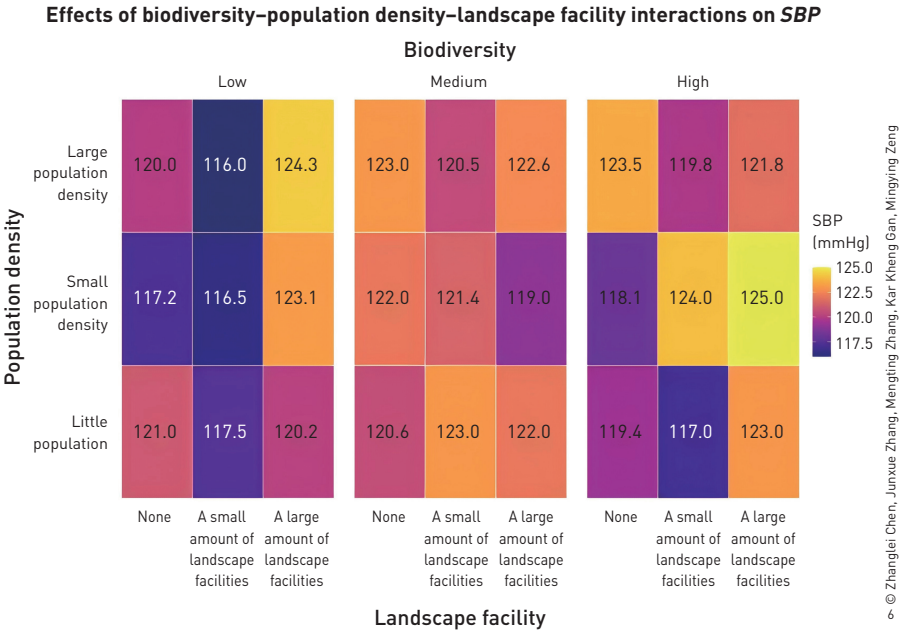


Fig. 5 The heatmap of the interaction effects of environmental indicators on cognitive stress.

Fig. 6 The heatmap of the interaction effects of environmental indicators on *SBP*.

4 Discussion

4.1 The Impacts of Different Degrees of Landscape Complexity on Physiological, Psychological, and Cognitive Dimensions of Health

This study aimed to compare the psychological and physiological recovery before and after exposure to campus green space of varied landscape complexities through VR simulations. The findings indicated that all 27 complexities of campus green spaces are conducive to physical and mental recovery.

Building on this confirmation of the general benefit, a more nuanced analysis revealed how specific dimensions of landscape complexity differentially shape restorative outcomes. The integrated results highlighted three key patterns: 1) biodiversity served as a robust, broad-spectrum restorative factor, associated with lower physiological arousal and enhanced positive cognitive states such as interest and relaxation; 2) population density predominantly exhibited stress-inducing effects, correlating with elevated physiological markers, increased cognitive stress, and reduced engagement; and 3) crucially, the impact of landscape facility was not linear but highly context-dependent, moderated by the existing levels of biodiversity and population density. Consequently, the most restorative environments emerge not from maximizing any single element, but from specific configurational synergies, particularly the combination of high biodiversity, low population density, and moderate facility provision.

Consistent with its identification as a broad-spectrum restorative factor, the impact of biodiversity on cognitive recovery was striking, notably influencing calmness, cognitive stress, relaxation, boredom, and interest. As biodiversity increased in the virtual setting, cognitive stress and excitement improved, while boredom diminished. The recovery performance of biodiversity on physiological indicators was also very significant: it significantly affected physiological indicators, leading to reductions in *HR*, *SBP*, and *DBP*, corroborating findings by Yuliya Linhares et al. regarding biodiversity's health benefits[61]. This resonates with the concept of biophilia, as higher biodiversity aligns with enhanced human recovery, consistent with prior scholarly observation[23,62–63]. In this research, greater biodiversity positively impacted participants' physical and psychological recovery, resonating with numerous practices where exposure to nature, such as green plants in office and retail and service environments[64–65], contributes to relaxation and well-being.

However, it is important for this research to acknowledge Martin Dallimer et al.'s study[21], whereby it revealed no correlation between changes in biodiversity and the environment's restorative quality. It may be due to participants' self-selection bias, which might not adequately represent the broader population[66]. In addition, it is also worth noting that Birgitta Gatersleben and Matthew Andrews' study yielded conflicting outcomes compared with our findings, possibly due to the distinctive study setting in a national forest park in the United Kingdom. Unlike meticulously maintained campus landscapes, this natural sanctuary embodies a biologically diverse and intricate wilderness that inherently triggers a sense of imminent danger, prompting an instinctual readiness to flee[67]. The discrepancy between our findings and previous research could be rooted in differences in survey samples. Moreover, it might be because campus green spaces, compared with national forests, are artificially and distinctly structured with a more organized spatial arrangement of greenery that little evokes negative cognitive states such as nervousness, panic or distraction[66].

In contrast, aligning with its characterization as a predominantly stress-inducing dimension, population density notably impacted cognitive recovery, significantly influencing feelings of calm, tension, disturbance, and relaxation. Population density also affected physiological recovery, with larger population correlating with poorer recovery. The interaction heatmaps provided a more nuanced understanding, unequivocally identifying high population density as the most consistent environmental risk factor, leading to elevated *SBP* across nearly all configurations. These findings align with previous studies indicating that larger population density in environments hindered physical recovery, sometimes leading to adverse effects[57,68–69]. Interestingly, cognitive recovery was notably better in spaces with a smaller population compared with unoccupied ones. Mintai Kim et al.'s research highlighted that an empty landscape environment on campus at night can evoke fear and tension[70]. While larger crowds often imply increased social interaction, they can also trigger anticipated psychological stress and cognitive strain, particularly among students seeking solitude in campus landscapes to alleviate stress. Nonetheless, these green spaces harbor natural threats like poisonous animals, weather risks such as lightning, and the potential threat of encountering criminals. The perception of a hazardous environment tends to evoke heightened negative cognitive state[71–73].

The presence of landscape facilities influenced emotional and cognitive recovery, but this influence was highly context-dependent. While participants on average reported higher relaxation in scenes with facilities compared with those without, the heatmaps qualify that: in low-density, serene environments, the introduction of facilities could be perceptually disruptive, whereas their value in alleviating boredom and *SBP* was most pronounced in already crowded and biodiverse areas. Therefore, landscape facility did not exert a uniform, significant main effect on emotions across all contexts; its impact was modulated by population density and biodiversity. Its impact on physiological signals was less pronounced, only showing an association with *SBP* fluctuations. Yet, in terms of cognitive recovery, landscape facility demonstrated the most significant effect, notably influencing cognitive states of boredom, visual attention, attention, cognitive stress, and excitement. Specifically, boredom, attention, and visual attention were notably higher when landscapes lacked elements, while cognitive stress and excitement increased with the introduction of landscape facilities. Critically, interaction analyses revealed a clear "dose-threshold" effect in urban high-density areas, where an initial increase in facilities could be detrimental before becoming beneficial. Conversely, in low-density serene environments, their introduction was often disruptive. This nuanced interplay explains why a simple "more is better" rule does not apply.

These findings align with prior research indicating that environments with more landscape elements enhance recovery performance[12,28,59,74]. However, there is yet a definitive or consistent academic consensus on the relationship between landscape complexity and user preference. Caroline M. Hagerhall study revealed a preference for moderate landscape complexity, indicating an inverted U-shaped relationship between the preference for natural landscapes and the degree of landscape complexity[17]. This

variation in preferences might be contingent on different landscape styles[75–77]. Our results extend this understanding by specifying the contingency: within campus green spaces, the restorative outcome of "more landscape elements" (i.e., landscape facilities) is not guaranteed but is conditional upon the social (i.e., population density) and ecological (i.e., biodiversity) setting, supporting a configurational rather than an additive model of landscape complexity.

4.2 The Relationships Between Landscape Complexity, Health, and Design

These nuanced patterns culminate in a central design implication: restorative quality arises from configurational synergy, not isolated elements. In this study, we discovered that highly restorative campus green spaces boast rich environmental biodiversity. For college students seeking daily respite, it is essential for campus landscapes to possess abundant plant species and density. Our findings suggest that aiming for a plant species richness demonstrably higher than the typical levels quantified in our campus audit is a robust target for achieving high restorative benefit. This should particularly emphasize the presence of diverse vegetation structures, which in our experimental settings contributed to creating visually rich and engaging environments that supported positive affective states.

Furthermore, it is crucial to improve fundamental public amenities such as night lighting seating areas, and shelters or shade structures. The experimental findings indicate that an "abundant" level of facilities is associated with reduced boredom and heightened engagement. However, the implementation strategy must be informed by context. For instance, facilities should be concentrated in areas that are already biodiverse and have higher pedestrian traffic, where they can better mitigate the negative effects of crowding and enhance engagement. In such areas, the strategic placement of shelters or shade structures can further support this goal by providing respite and fostering positive social encounters. In quiet, low-traffic zones intended for solitude and deep reflection, the provision of minimalist facilities is preferable to avoid introducing disruptive elements. Here, if provided, any sheltering elements should be designed to be visually permeable and integrated into the natural surroundings to minimize intrusion. Incorporating a variety of well-designed landscape features can further enrich the sensory appeal and functionality of these spaces, which not only diversifies the scene but also augments the array of landscape facilities available.

Zoning is another crucial consideration during the initial phase of campus development. Spaces dedicated to learning, such as teaching buildings and study areas, should differ in design from leisure and living areas[37]. Environments characterized by high biodiversity, extensive crowds, or an abundance of landscape facilities can inadvertently distract individuals leading to reduced attention and increased cognitive strain, hence impacting learning efficiency[39–40]. Therefore, when designing landscapes in educational settings, spaces intended for study and classes should prioritize simplicity and spaciousness, aiming for complexity levels at or below the campus average. Excessive flora and fauna or an overload of engaging landscape elements should be avoided in these spaces to prevent unnecessary distractions[38,40,78]. Conversely, social and leisure zones should target the "high" complexity parameters defined above to maximize restorative outcomes. The optimal design, as suggested by the interaction effects on cognitive stress in this research, might even involve a hybrid approach: creating zones of high biodiversity and low population density but incorporating a small amount of well-designed facilities to provide a subtle positive stimulus and achieve the lowest cognitive stress levels.

4.3 Limitations and Prospects

This study encounters several limitations.

1) Our investigation into environmental perception relied on monitoring physiological, psychological, and cognitive indicators, yet the temporal effectiveness of environmental recovery over an extended period requires further exploration due to the temporal inconsistencies in psychological and physiological recovery.

2) The wrist-based BP monitor used in this study, while practical for capturing dynamic trends in controlled experiments, may have lower absolute accuracy compared with validated, cuff-based clinical sphygmomanometers. Our interpretations therefore focus on the directional trends and comparative differences in physiological responses across conditions, rather than on the precise clinical values of the readings. Furthermore, the interpretation of short-term alterations in autonomic indicators such as *HR* and *BP* is complicated by multiple factors, including individual genetic traits, posture during measurement, and transient environmental conditions. Prior research indicates that the magnitude of change in these measures only partially reflects the extent of stress relief. While our findings demonstrate that varying landscape complexity elicits differential short-term reductions in *BP*, it remains uncertain whether these changes are driven solely by perceived stress reduction or involve other concurrent physiological pathways.

3) Despite efforts to maintain an undisturbed laboratory environment during the experiments, factors like temperature and noise could potentially influence participants' physical and mental recovery performance.

4) The 1-minute exposure per VR scene was chosen to capture the immediate, initial psychophysiological response trend across a wide range of conditions. While sufficient for detecting significant differential effects and aligned with protocols assessing rapid affective and autonomic responses to visual stimuli, this duration may not be sufficient for all physiological indicators, particularly *BP*, to reach a fully stabilized post-stress baseline. Future studies employing longer exposure durations (e.g., 5 or 10 min) would be valuable to examine the sustainability and later phases of the recovery process initiated by different landscape settings. Furthermore, considerations regarding the experimental protocol itself should be noted. The intensive, repeated-measures design, while necessary for within-subject comparisons across multiple conditions, may have induced some degree of participant fatigue over its approximately 47-minute duration. Although we implemented full randomization of scene order to distribute any potential time-on-task effects evenly across conditions, a gradual drift in attention or baseline physiological state over the course of the experiment cannot be entirely ruled out and may contribute to increased data variability.

5) While our sample primarily comprised current college students, in which enhancing its representativeness, inherent differences in personal experiences and spatial preferences among individuals could still affect the physical and psychological data. Besides, in terms of the sample selection, while the stringent eligibility criteria ensured a healthy participant cohort and the stress-induction protocol created a uniform high-stress baseline, we did not systematically analyze participants' demographic characteristics (e.g., gender), academic pressures (e.g., year of study, academic discipline), or pre-existing stress profiles (e.g., habitual exposure to green spaces in non-experiment environments, baseline chronic stress levels). This homogeneity was beneficial for initial controlled exploration by reducing noise from extraneous individual differences. However, it also limits the generalizability of our findings. Future studies could incorporate detailed questionnaires to assess these traits and examine their role as potential moderators of restorative outcomes, thereby addressing the question of "for whom" certain landscape configurations are most effective.

6) While VR scenes can emulate real-life experiences to a certain extent, future research could investigate the impact of multisensory experiences on environmental restoration effects in green spaces by incorporating additional sensory experiences such as hearing, touch, and smell parallel to visual stimuli to establish more realistic environmental perception experiments. Additionally, the experimental scenes were exclusively modeled on a teaching building atrium, a setting selected based on preliminary research indicating its role as a common stress-inducing locale. Future investigations should examine how the interplay between other campus green space types (such as athletic fields and dedicated contemplation gardens) and landscape complexity modulates restorative outcomes.

5 Conclusions

This study evaluated the restorative potential of campus green spaces with varying complexities by analyzing physiological, psychological, and cognitive signals within a controlled VR environment. The landscape complexity of these spaces was characterized through biodiversity, population density, and landscape facility. By constructing 27 intricately designed virtual scenes, this research facilitated a controlled investigation of these variables across defined gradients, which helped minimize disruptive factors. This VR-based approach allowed for the immersion of participants in diverse settings where multiple health indicators (e.g., S-AI scale, *HR*, *BP*, EEG) were synchronously monitored, offering a replicable methodological pathway for related research. The findings indicated that green spaces contribute positively to the physical and mental well-being of students, aligning with prior research outcomes. Landscape complexity of campus green space showed significant associations with physiological signals (*HR*, *DBP*, and *SBP*), psychological signals (calm, nervous, relaxed, disturbed, contented, and annoyed), and cognitive signals (boredom, visual attention, attention, interest, excitement, engagement, relaxation, focus, cognitive stress, and stress).

This study offers a reconceptualization of landscape complexity for academic settings. Conceptually, we reframe complexity not as an aesthetic attribute but as a cognitive resource to combat depletion and facilitate recovery at the source of academic stress. This represents a paradigm shift from viewing landscapes as merely "scenery" to understanding them as essential cognitive-supportive infrastructure for the high-demand academic population, positioning campus landscapes not as an escape but as an integrated part of the academic ecosystem. Methodologically, we employ a multi-dimensional EEG framework that dissects restorative experiences into granular cognitive states, revealing the specific mechanisms through which different complexities influence mental function. Practically, this synergy yields a precision design guide for creating "cognitive niches"—zones where calibrated complexity targets specific deficits, such as using biodiversity to reduce boredom and renew motivation, thereby directly supporting

the cognitive ecology of learning.

Specifically, biodiversity demonstrated positive correlations with relaxed and contented psychological signals, as well as cognitive stress, interest, and relaxation among cognitive signals. Conversely, it exhibited negative correlations with calm, nervous, and disturbed psychological signals, *HR*, *SBP*, and *DBP* among physiological signals, and boredom in cognitive signals. Population density showed positive correlations with nervous psychological signals, *HR*, *SBP*, and *DBP* in physiological signals, and stress and cognitive stress in cognitive signals. In contrast, it displayed negative correlations with calm, relaxed, and contented psychological signals, as well as boredom and engagement in cognitive signals. Landscape facility indicated positive correlations with contented psychological signals, cognitive stress, and excitement in cognitive signals, while demonstrating negative correlations with disturbed psychological signals, *SBP* in physiological signals, and boredom, attention, and visual attention in cognitive signals.

On the whole, higher levels of biodiversity and landscape facility positively influenced the health of college students, albeit contributing to increased cognitive stress. In contrast, population density demonstrated an inverse relationship with health benefits. Nonetheless, maintaining a low population density is essential, as studies indicate that vacant environments are not conducive to recovery. Most importantly, our findings emphasize that these factors do not operate in isolation. The optimal restorative environment emerges from a specific synergy: high biodiversity and low population density form the essential foundation, while the strategic, context-aware integration of landscape facilities can then fine-tune this environment to achieve peak restorative efficacy, particularly for cognitive recovery. This suggests that creating a highly restorative campus green space involves enhancing environmental biodiversity, incorporating engaging landscape vignettes and essential public facilities, while carefully managing population density to avoid congestion.

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基于虚拟现实与脑电分析的校园绿地景观复杂度对学生健康的影响

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摘要

校园绿地是缓解学生压力的关键恢复性场所，如何营造健康校园环境已成为日益关注的热点议题。然而，校园绿地要素对学生恢复性潜力的具体影响程度仍有待深入探究。本研究整合虚拟现实技术、脑电指标及其他生理测量手段，通过控制性实验，从生物多样性、人群密度及景观设施3个维度探索了景观复杂性对大学生身心健康的影响。研究结果表明，较高的生物多样性预示着较低的生理应激水平与更积极的认知状态；人群密度会显著提升受试者的收缩压并加剧认知压力；景观设施的作用与社会情境密切相关，拥挤环境能有效缓解无聊感，但在低密度区域其增益效应则有所减弱。交互分析结果显示，“高生物多样性、低人群密度及适量的景观设施”是对认知恢复的最优环境配置。本研究打破了单一维度的设计视角，提出了一种以生态丰富性为基底、审慎调控社交密度、将人工设施作为情境性增强要素的设计路径。这一发现通过阐明校园环境下的感知作用机制，完善了现有的恢复性环境理论模型，为营造具有认知支持功能的校园生态系统提供了循证依据。

关键词

环境感知；恢复性环境；景观复杂性；校园绿地；身心健康；脑电指标；虚拟现实

文章亮点

- 生物多样性持续促进环境恢复，可有效降低生理应激水平并提升积极认知参与
- 人群密度对恢复效果呈非线性制约，过度密集与完全空置均不利于健康增益
- 景观设施呈现情境依赖性，其效益受生物多样性水平与人群密度共同调节
- 以高生物多样性结合低人群密度为基础，辅以策略性配置的景观设施，可实现最优的恢复效益
- 本研究构建了一套多维联动、作用机制明晰的分析框架，为循证导向的环境设计提供了支撑

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