

Effects of Perceived Biodiversity on Human Health Restoration Benefits in Pocket Parks

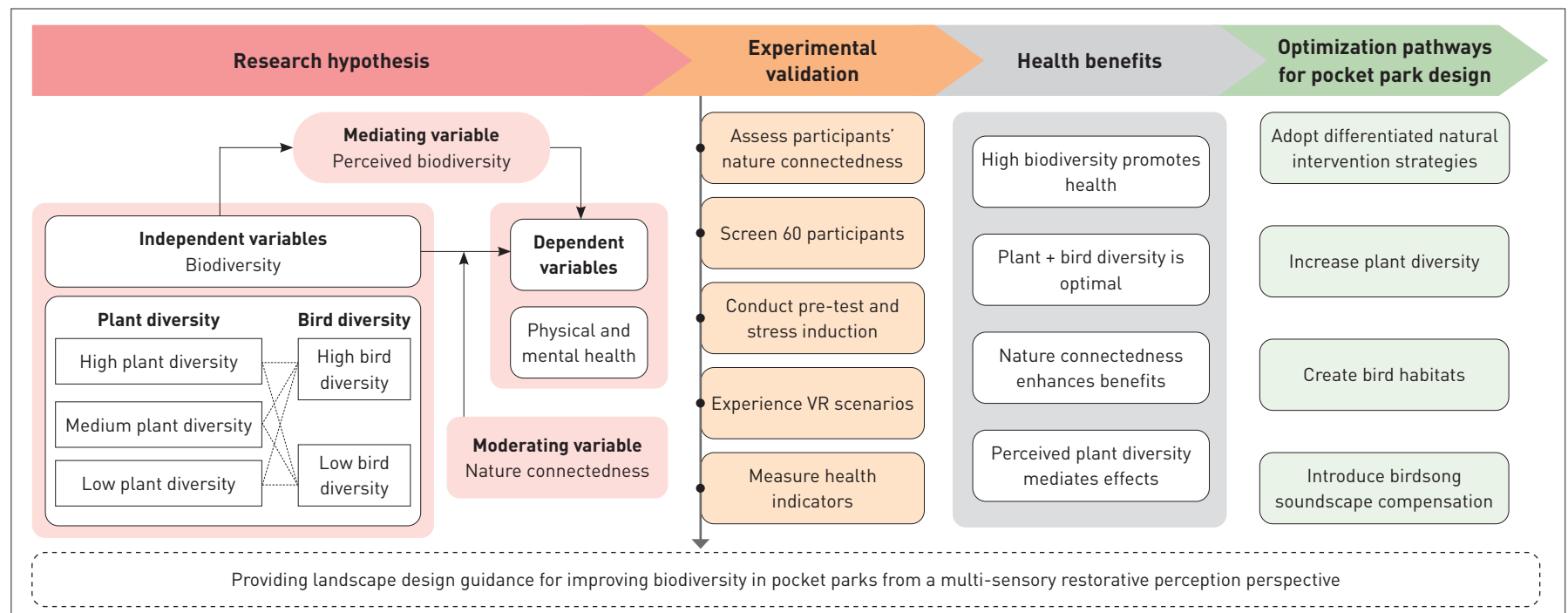
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GRAPHICAL ABSTRACT



ABSTRACT

Diverse biotic components in urban green spaces not only provide fundamental conditions for environmental adaptation but also confer substantial benefits to human health. However, few studies have explored the health benefits of biodiversity in pocket parks—a specific type of urban green space—from the perspective of audio-visual interaction. This study adopted plant diversity (high, medium, and low) as the visual independent variable and bird diversity (high and low) as the auditory independent variable within the biodiversity framework, and constructed six virtual biodiversity scenarios in pocket parks. A total of 60 participants were recruited, and each participant was randomly assigned to

experience two distinct biodiversity scenarios. Heart rate variability and psychological scales, including the Profile of Mood States, Perceived Restorativeness Scale, and Perceived Biodiversity Scale, were measured to examine the restorative effects of different types and levels of biodiversity in pocket parks. The results indicate that: 1) rich plant and bird diversity exerts significant positive effects on human health; 2) the combined perception of high plant diversity and high bird diversity produces the strongest restorative benefits; 3) perceived plant diversity as the primary mediating pathway in the impact of biodiversity on mental health; and 4) individuals with higher nature connectedness gain greater restorative benefits in

environments with higher biodiversity. Therefore, in the optimal design of pocket parks, improvements should be made to enhance plant and bird diversity, create suitable habitats, implement soundscape compensation, and adopt differentiated intervention strategies to leverage the health promoting effects of green spaces. The study provides a reference for enhancing plant and bird diversity in pocket parks and contribute significantly to improving the health promoting capacity of urban green spaces.

KEYWORDS

Biodiversity; Urban Green Space; Audio–Visual Interaction; Pocket Park; Human Health; Plant Diversity; Bird Diversity

HIGHLIGHTS

- Confirms the combined effect of high plant and bird diversity on physical and mental recovery
- Reveals the mediating mechanism by which biodiversity influences health through the perceived plant diversity
- Provides new evidence for health interventions for groups with different levels of nature connectedness
- Supports the design of audio–visual environments in pocket parks based on biodiversity

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1 Introduction

Against the backdrop of rapid urbanization, urban environmental degradation has intensified, severely impacting ecosystem functions^[1]. Issues pertaining to ecosystem health, such as habitat fragmentation and biodiversity loss, are occurring with increasing frequency^[2], posing significant threats to human well-being^[3]. Biodiversity, a crucial natural component of urban green spaces,

not only enhances the adaptive capacity of ecosystems but also provides ecosystem services, for human populations^[4-5], such as air purification and microclimate regulation, yielding multifaceted health benefits^[6-7]. Prior research indicates that landscapes with higher biodiversity are more likely to elicit positive emotions and mitigate negative ones, such as anxiety and depression^[8]. Edward Osborne Wilson's Biophilia Hypothesis, proposed in 1984, further illuminates the innate human preference for biological elements^[9].

In the study of the health benefits of biodiversity, cross-sectional approaches are predominantly employed in international research^[10]. Findings largely indicate a strong positive correlation between regional biodiversity levels and residents' mental health^[7,11]. To further elucidate underlying mechanisms, experiments are often conducted in real-world settings^[12-13], exploring the relationship between specific biodiversity metrics and restorative outcomes. Among these, plants and birds serve as the most common indicators^[14], with metrics like species richness and evenness being key measures of biodiversity in green spaces^[5,15]. Other studies have utilized butterflies or mammals^[13,16-17] as indicator species. A consensus suggests a significant positive correlation between bird species richness and emotional or mental health, whereas bird abundance shows no such associations with well-being^[11,18].

Compared with actual biodiversity, virtual biodiversity involves simulating realistic biodiversity scenarios through media like photographs, videos, audio^[19-20], and virtual reality (VR) to provide immersive, interactive sensory experiences^[21]. Laboratory studies frequently adopt this method. Research demonstrates that virtual biodiversity can also deliver effective restorative benefits^[21]. While these studies, ranging from macro to micro scales, provide a scientific foundation for detailed investigations into the health effects of biodiversity, issues like ambiguous classification boundaries or a lack of scientific rationale in level delineation persist in the stratification of biodiversity levels^[20,22]. Therefore, a more in-depth exploration of the restorative effects across various biodiversity indicators and levels is warranted to offer more practical guidance for biodiversity sensitive design.

In contrast to objective biodiversity, perceived biodiversity refers to individuals' subjective assessment of living organisms in real or simulated environments^[13]. Both actual biodiversity and individual differences can influence the health outcomes associated with perceived biodiversity^[23-24]. Some studies indicate that perceived biodiversity is a stronger predictor of psychological well-being than actual biodiversity^[13,25]. For instance, Simone Farris found that individuals who noticed ground cover and trees

in environments with the same biodiversity level reported more positive emotions^[26]. Conversely, Lingshuang Meng et al. suggested that higher native plant diversity might negatively correlate with perceived biodiversity, potentially hindering restoration^[23]. However, the internal mechanisms by which perceived biodiversity mediates the health effects of actual biodiversity remain insufficiently validated, and few studies have specifically examined the health effects and mediating role of perceived biodiversity itself.

Senses do not operate in isolation; instead they interact to form a holistic perception of the environment. Compared with single-sensory experiences, multi-sensory perception yields more significant health benefits^[27]. However, most existing studies on examining restorative benefits of biodiversity in green spaces are based on a single sensory modality^[26,28]. In the perceptual assessment of plant diversity, the visual channel contributes more significantly than other senses^[16,29]. Bird diversity is primarily perceived through the auditory channel. Yuqi Liu et al. found that even simulated bird sounds can significantly enhance visitors' pleasure^[30]. Further research indicates that visual landscapes can alter the perception of soundscapes; a positive visual scene can effectively mask negative auditory experiences, thereby improving overall environmental perception^[31]. Conversely, pleasant natural sounds can also mitigate negative visual perceptions and elicit positive emotions^[3]. Currently, there is limited empirical research investigating the effects of biodiversity on human health from a multi-sensory perspective, highlighting the need to further explore the mechanisms underlying the health promoting effects of biodiversity in green spaces under multi-sensory interaction.

Regarding the selection of green space types, existing biodiversity studies have predominantly focused on urban parks, suburban parks, and campus green spaces^[18,21,32], with insufficient attention given to small scale green spaces. Pocket parks, representative of micro-green spaces in high-density built environments, utilize natural elements to aid in residents' stress recovery^[33]. Research also indicates that the biodiversity characteristics and restorative mechanisms of pocket parks differ from those of other urban green space types^[8]. The *2024 Pocket Park Construction Guidelines (Trial)* ("the Guidelines" hereafter) emphasizes introducing diverse plants and ecological design into pocket parks. Enhancing biodiversity in pocket park design is therefore particularly important for improving residents' physical and mental health.

Based on the above research status and gaps, this study argues that investigating the health benefits of biodiversity from

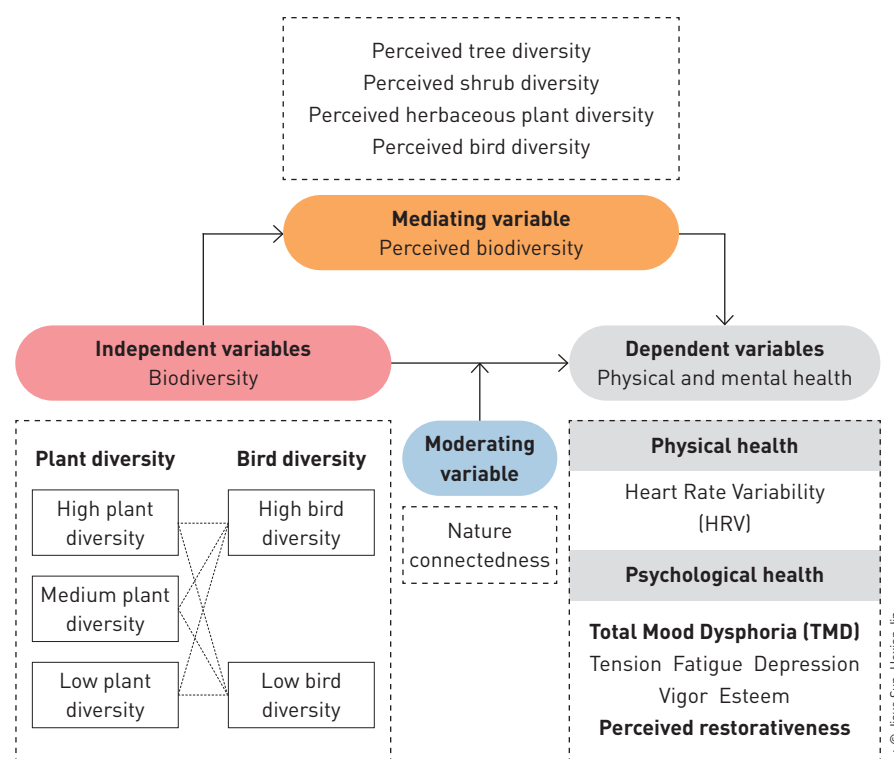
an audio-visual interactive, multi-sensory perspective holds significant theoretical and practical importance. Selecting "plant diversity" and "bird diversity" as key biodiversity indicators, this study establishes virtual audio-visual environments of pocket parks to explore the internal mechanisms linking biodiversity in pocket parks to resident health under audio-visual interaction. The study aims to address the following questions (Fig. 1): 1) Do plant diversity and bird diversity in pocket parks impact human physical and mental health? 2) Under audio-visual interaction, do different combinations of biodiversity levels have significantly different effects on human health benefits? 3) Are the health benefits of virtual biodiversity mediated by perceived biodiversity? And 4) do the health benefits of biodiversity differ significantly among individuals with varying levels of nature connectedness? Theoretically, this study aims to provide a new perspective for research on the health benefits of urban green spaces. Practically, it seeks to offer a reference for biophilic design in pocket parks.

2 Research Methods

2.1 Virtual Biotic Audio-Visual Factors and Scenario Design

This study used a pocket park as the baseline environment, with plant diversity as the visual independent variable and bird

Fig. 1 Variables and hypotheses in the experiment design.



diversity as the auditory independent variable. Based on existing research, plant diversity is categorized into high, medium, and low levels^[34–35], while bird diversity is classified into high and low levels^[25,36]. Using VR technology, experimental scenarios representing these different levels of plant and bird diversity were created.

2.1.1 Visual Biotic Factors

According to the Guidelines, the typical size of a pocket park ranges 400–10,000 m², the virtual environment for this experiment was set within a 50 m × 50 m area (2,500 m²). Only minimal features, such as a simple plaza and seating, were included to avoid interference from non-experimental factors. Three visual scenarios representing high, medium, and low plant diversity were created by varying the composition of plant species (Fig. 2). Based on field surveys and model calibration, the ratio of trees, shrubs, and herbaceous plants was approximately 1:1:2. The scenes were modeled in SketchUp 2019, and vegetation placement and material rendering were completed using the D5 Render platform. The final panoramic images were presented via VR equipment. Compared with viewing static images, VR-based immersive experiences offer greater realism and yield more scientifically reliable results^[21].

To overcome the limitations of ambiguous quantification in traditional studies on perceived biodiversity and restorative benefits, this study employed the Shannon Diversity Index (SDI) as



Fig. 2 Visual scenes of high, medium, and low plant diversity levels.

the metric to define different levels of plant diversity. This enhances the rigor of the experimental design and the scientific validity of the results. The *SDI* quantifies plant diversity levels by incorporating both species richness and evenness^[37]. The formula is as follows:

$$H = -\sum_{i=1}^n P_i \ln P_i \quad (1)$$

In the equation, P_i represents the relative abundance of the i -th species; H denotes the plant diversity of the community. Based on the research team's biodiversity survey of pocket parks in East China and existing literature, the *SDI* of urban small green spaces typically ranges between 1.5 and 3.2^[38]. To eliminate the confounding effect of plant abundance on the *SDI* calculation, the high and medium plant diversity scenarios maintained a constant number of individual plants (372 individuals). The high diversity scenario included 25 plant species, while the medium diversity scenario included 6 species. The low diversity scenario, represented by a hard plaza space with none plants, served as the experimental control. The *SDI* values for the high, medium, and low plant diversity levels were 3.03, 1.71, and 0.00, respectively (Table 1). All selected plants are common horticultural species in East China. To minimize the

Table 1: Composition of plant species across different levels of plant diversity

No.	Plant type	Species name	Quantity	SDI
Visual scenario of high plant diversity				
1	Evergreen tree	<i>Osmanthus fragrans</i>	11	0.12
2		<i>Camphora officinarum</i>	9	0.10
3	Deciduous tree	<i>Acer palmatum</i>	5	0.07
4		<i>Ginkgo biloba</i>	13	0.13
5		<i>Prunus serrulata</i>	9	0.10
6		<i>Hibiscus mutabilis</i>	10	0.11
7		<i>Celtis sinensis</i>	3	0.04
8		<i>Sapindus mukorossi</i>	3	0.04
9	Evergreen conifer	<i>Cedrus deodara</i>	7	0.08
10	Evergreen shrub	<i>Ligustrum quihoui</i>	10	0.11
11		<i>Pittosporum tobira</i>	8	0.09

(Continued)

Table 1: Composition of plant species across different levels of plant diversity (Continued)

No.	Plant type	Species name	Quantity	SDI
Visual scenario of high plant diversity				
12	Foliage shrub	<i>Nandina domestica</i>	5	0.07
13		<i>Ligustrum sinense</i>	11	0.12
14		<i>Buxus megistophylla</i>	5	0.07
15		<i>Aucuba japonica</i> var. <i>variegata</i>	18	0.16
16		<i>Loropetalum chinense</i> var. <i>rubrum</i>	10	0.11
17	Flowering shrub	<i>Gardenia jasminoides</i>	15	0.14
18		<i>Rhododendron simsii</i>	15	0.14
19	Evergreen herb	<i>Ophiopogon japonicus</i>	40	0.26
20		<i>Reineckea carnea</i>	30	0.22
21		<i>Ophiopogon bodinieri</i>	22	0.19
22		<i>Nephrolepis cordifolia</i>	50	0.29
23	Flowering herb	<i>Viola tricolor</i>	16	0.15
24		<i>Iris tectorum</i>	22	0.19
25		<i>Hydrangea macrophylla</i>	25	0.20
Total			372	3.03
Visual scenario of medium plant diversity				
1	Evergreen tree	<i>Camphora officinarum</i>	45	0.28
2	Deciduous tree	<i>Sapindus mukorossi</i>	25	0.20
3	Flowering shrub	<i>Loropetalum chinense</i> var. <i>rubrum</i>	65	0.33
4	Evergreen shrub	<i>Ligustrum quihoui</i>	32	0.23
5	Evergreen herb	<i>Ophiopogon japonicus</i>	145	0.36
6	Flowering herb	<i>Hydrangea macrophylla</i>	60	0.32
Total			372	1.71
Visual scenes of Low plant diversity (control group)				
0			0	0.00

excessive interference of color variables on psychophysiological measurements, the foliage and flower colors of the plants were limited to red, yellow, and green color schemes.

2.1.2 Auditory Biotic Factors

Research indicates a negative correlation between bird diversity and traffic noise, with bird populations declining most significantly in areas of high traffic volume^[39]. Furthermore, the vocalizations of birds whose calls overlap in frequency with noise are subject to acoustic masking^[40]. Therefore, urban noise is considered a typical sound environment for low bird diversity^[36]. Additionally, smaller green spaces lead birds to adopt a more stochastic foraging pattern, often resulting in a higher proportion of omnivorous species^[41], a finding consistent with preliminary surveys of pocket parks. In this study, bird richness is used as the indicator for bird diversity. Bird calls from five common species in East China pocket parks—*Acridotheres cristatellus*, *Aegithalos concinnus*, *Copsychus saularis*, *Spilopelia chinensis*, and *Sinosuthora webbiana*—were combined to constitute the high bird diversity auditory stimulus. Conversely, a composite of urban noise was used as the low bird diversity stimulus^[42] (Table 2).

Table 2: Composition of sound types for different levels of avian diversity

No.	Bird name	Habitat type	Foraging type	Activity period
High bird diversity auditory scenario				
1	<i>Acridotheres cristatellus</i>	Shrubs, herbaceous plants	Omnivorous	Diurnal vocalization
2	<i>Aegithalos concinnus</i>	Shrub	Omnivorous	Dawn chorus
3	<i>Copsychus saularis</i>	Trees, herbs	Omnivorous	Dawn chorus
4	<i>Spilopelia chinensis</i>	Shrubs, herbaceous plants	Herbivorous	Crepuscular activity
5	<i>Sinosuthora webbiana</i>	Trees, shrubs	Omnivorous	Diurnal vocalization
Low bird diversity auditory scenario				
Traffic noise; human voice noise				

NOTE

Source of the information: Ref. [42].

$$TMD = T + F + D - (V + E) + 100. \quad (2)$$

2.2 Recruitment of Participants

A total of 60 participants were recruited for this experiment via posters. The average age was 22.27 ± 2.93 years, with 41% male and 59% female. All participants had normal vision and hearing, as well as normal color vision.

2.3 Experimental Equipment and Measurement of Indicators

2.3.1 Connectedness to Nature Scale

The Connectivity with Nature Scale (CNS) was used to measure participants' nature connectedness. The CNS is a unidimensional scale consisting of 14 items, designed to measure individuals' overall experience of connection to nature and their emotional attitudes towards it. Responses were recorded on a 5-point Likert scale ranging from 1 (very little) to 5 (very much), with items No. 4, 12, and 14 being reverse-scored. A higher total CNS score indicates a stronger sense of nature connectedness^[43].

2.3.2 Heart Rate Variability

The heart rate variability (HRV) module of the ErgoLAB system was used to collect participants' ECG data. The following HRV parameters were selected as indicators: average heart rate (AVHR), root mean square of successive differences (RMSSD), and the low frequency/high frequency ratio (LF/HF). AVHR, a key physiological indicator of emotional valence, shows a positive correlation with negative emotions (e.g., anxiety, depression) when increased, and suggests positive emotional experiences when decreased^[44]. RMSSD values assess physiological stress; an increase indicates a state of stress recovery, while a decrease suggests heightened physiological stress^[45-46]. An increase in the LF/HF ratio signifies a rise in negative emotional arousal^[47-48].

2.3.3 Profile of Mood States

The Profile of Mood States (POMS) was used to evaluate participants' emotional states. The scale comprises 40 items across seven emotional factors: tension, anger, fatigue, depression, confusion, vigor, and esteem. It employs a 5-point Likert scale from 1 (very little) to 5 (very much)^[28]. Emotional changes and the participants' emotional states were assessed based on the total mood dysphoria (TMD) score. A higher TMD score indicates stronger negative emotions, while a lower score indicates a more stable emotional state. Since field research revealed that the public rarely experiences panic or anger, this study selected only five emotional factors—tension, fatigue, depression, vigor, and esteem—to assess participants' psychological well-being. The calculation formula is as follows:

2.3.4 Perceived Restorativeness Scale

This study adopted the Perceived Restorativeness Scale (PRS) developed by Terry Hartig. Its four subscales correspond to the core elements of Stephen Kaplan's theory of restorative attention^[12]: "Compatibility" refers to the extent to which the environment supports an individual's intended activities. Since preliminary field surveys indicated a weak association between biodiversity richness and site compatibility in this context, the present study used only three dimensions of the PRS for assessment: Being Away, Fascination, and Extent.

2.3.5 Perceived Biodiversity Scale (PBS)

To evaluate Perceived biodiversity, participants were first exposed to environments with different biodiversity levels and then asked to make an assessment. This study used the question, "How high or low do you perceive the diversity of a specific biotic component in this environment?" Participants rated the perceived diversity of trees, shrubs, herbaceous plants, and birds in the virtual environment on a 5-point Likert scale from 1 (very low) to 5 (very high). A higher total score indicates a higher level of perceived biodiversity, thereby quantifying participants' subjective assessment of biodiversity in a given scenario^[19]. The questionnaire demonstrated good reliability and validity, with a Cronbach's Alpha of 0.892, a KMO measure of sampling adequacy of 0.728, and a significant Bartlett's test of sphericity (*Sig.* < 0.001).

2.4 Conduct Experiments to Obtain Dependent Variables

Three levels of plant diversity and two levels of bird diversity were combined, resulting in 6 distinct audio-visual biodiversity scenarios: 1) high plant diversity + high bird diversity; 2) high plant diversity + low bird diversity; 3) medium plant diversity + high bird diversity; 4) medium plant diversity + low bird diversity; 5) low plant diversity + high bird diversity; and 6) low plant diversity + low bird diversity. Each scenario combination constituted an independent experimental group, totaling 6 groups. A total of 60 participants were recruited. Each participant was randomly assigned to experience and evaluate two different biodiversity scenarios, resulting in a valid sample size of 20 participants per group.

The experiment was conducted at the Donghu Campus of Zhejiang A&F University from November 25 to November 29, 2024, in a room with a constant temperature of 25°C. Upon arrival, participants were first briefed on the experimental procedure and

then completed a form with their basic personal information and the CNS^[45]. Subsequently, they wore the experimental equipment and rested quietly for 3 min.

The specific experimental procedure was as follows (Fig. 3). 1) Stress induction: participants engaged in 3 min of arithmetic calculations to induce physiological and emotional arousal. 2) Pre-test: participants completed the POMS. 3) Restorative experience: participants wore VR headsets for 4 min immersive experience in a virtual audio-visual environment. 4) Evaluation: based on their experience, participants completed the POMS, the PBS, and the PRS. This concluded the experiment for a single scenario, and the same process was then repeated for the second assigned scenario. The entire procedure was completed within 30 min.

2.5 Data Analysis

Experimental data were consolidated using Excel and then processed and analyzed using SPSS 26.0. Physiological data were categorized by experimental group. Data from the stress induction phase and the restorative phase were analyzed separately for each group. For the restorative experience phase, data from the middle 2 min were selected for detailed processing. To control for baseline differences, *HRV*, *TMD*, and their respective sub-metrics were calculated as the change scores (Δ values) between the restorative experience phase and the stress induction phase. In all subsequent analyses and tables, these change values are reported without the “ Δ ” symbol for brevity.

For the first research question, a main effects analysis was conducted to determine if different levels of biodiversity led to significant differences in restoration outcomes. If differences were found, post-hoc multiple comparisons and independent samples *t*-tests were used to compare the differences in physiological and psychological indicators between groups.

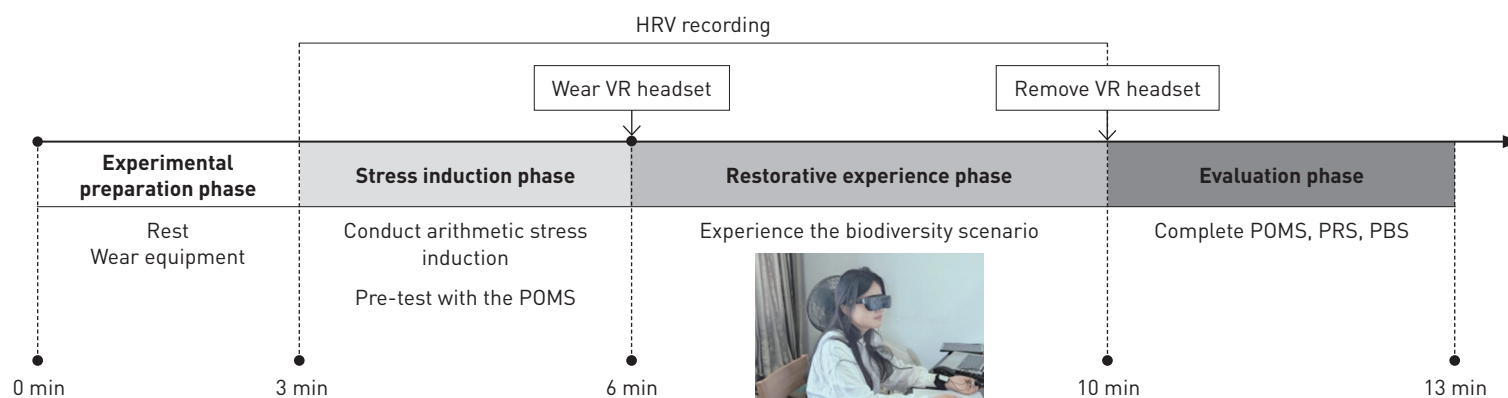
For the second research question, an interaction effect analysis

was first performed to test whether plant diversity and bird diversity had a significant interactive effect on the health indicators. If a significant interaction was found, a simple effects analysis was conducted to examine the health benefits of their interaction.

For the third research question, as the independent variables in this study are ordinal categorical variables, Spearman’s rank correlation analysis was first employed to examine the correlations between the independent variables (plant diversity and bird diversity), the dependent variables (perceived restorativeness, *TMD*), and the mediating variables (perceived biodiversity). If significant correlations were found, a hypothesized mediation model was constructed. A Bootstrap test (with 5,000 resamples) was then conducted to test the mediating effect of perceived biodiversity, thereby exploring the psychophysiological mechanism by which biodiversity affects physical and mental health through this pathway. In the mediation analysis model, the three levels of plant diversity and two levels of bird diversity were coded as dummy variables, while the mediating variable (perceived biodiversity) and the dependent variables (*TMD*) were treated as continuous variables.

For the fourth research question, to investigate the moderating effect of nature connectedness, participants were ranked from the highest to the lowest based on their CNS scores from the pre-test phase. They were then divided into four equal groups using the quartile method. Participants in the top 25% (first quartile) were defined as the high nature connectedness group, and those in the bottom 25% (fourth quartile) were defined as the low nature connectedness group. A simple effects test was performed on the high and low nature connectedness groups to analyze whether there were significant differences in their physiological indicator changes across different biodiversity levels.

Prior to all data analyses, tests for homogeneity of variance and normality were conducted, and all results met the requirements for parametric statistical tests.



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Fig. 3 Experimental procedure for a single scenario.

3 Results and Discussion

3.1 Higher Biodiversity Significantly Improve Physiological Stress and Emotional State

This research indicates that different levels of plant diversity and bird diversity significantly influence human health benefits.

3.1.1 High Plant Diversity Effectively Improves Physical and Mental Health

Following exposure to high and medium plant diversity, *RMSSD* values increased significantly, while *LF/HF* values showed a significant decreasing trend ($p < 0.001$). This suggests that higher plant diversity is conducive to improving stress states and reducing fatigue. In contrast, exposure to low plant diversity led to decreased *RMSSD* values (Fig. 4-1), increased *LF/HF* values (Fig. 4-2), and induced an increase in *AVHR* ($p < 0.001$) (Fig. 4-3), indicating that low plant diversity environments may promote heightened anxiety.

Compared with low plant diversity, high plant diversity significantly reduced negative emotions such as tension, fatigue, and depression, while simultaneously enhancing esteem and vigor ($p < 0.001$). The improvement effect on tension did not differ significantly between high and medium plant diversity ($p > 0.05$), but the effects on improving other emotions showed highly significant differences between groups ($p < 0.001$). Both medium and low plant diversity demonstrated a relatively weak effect on improving depression ($p > 0.05$). Low plant diversity was found to increase fatigue and diminish esteem (Fig. 4-4).

3.1.2 High Bird Diversity Promotes Greater Health Benefits

Significant between-group differences ($p < 0.001$) were observed in participants' physiological indicators and emotional valence under high and low bird diversity conditions. The high bird diversity scenario effectively reduced negative emotions such as tension, depression, and fatigue. Conversely, low bird diversity led to increased *AVHR* and *LF/HF* values (Figs. 5-1, 5-2), decreased

Fig. 4 The effects of plant diversity on physiological and psychological indicators.

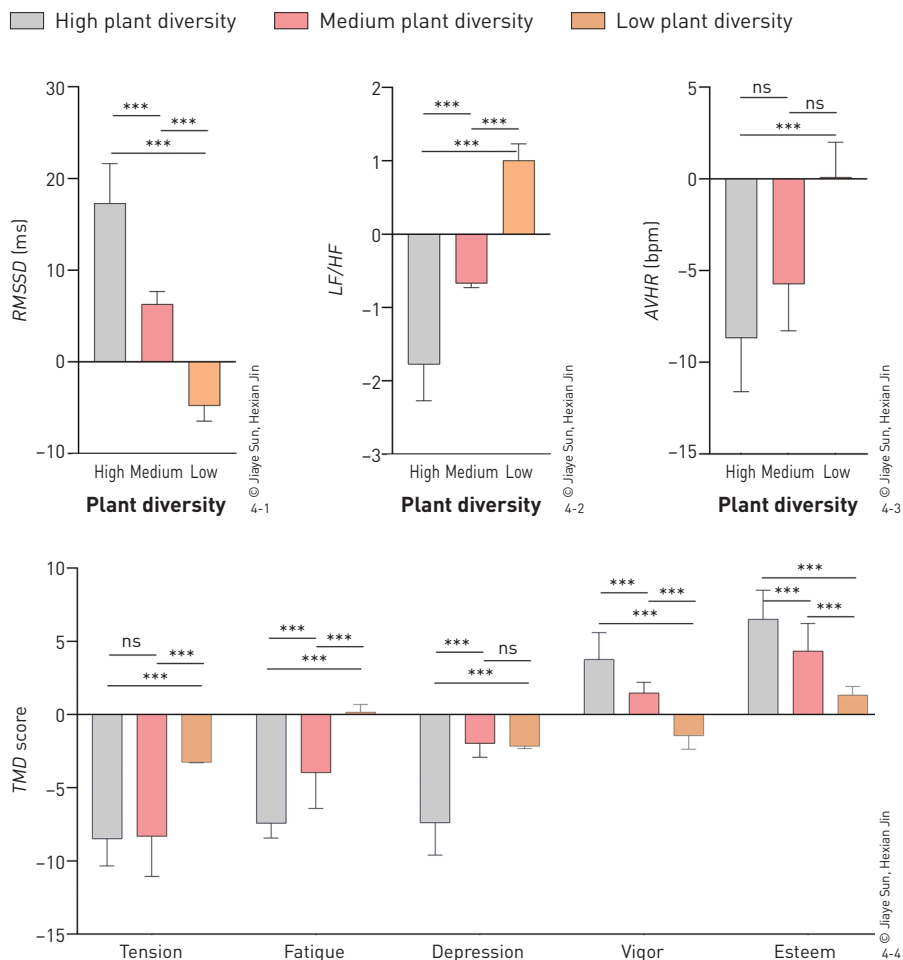
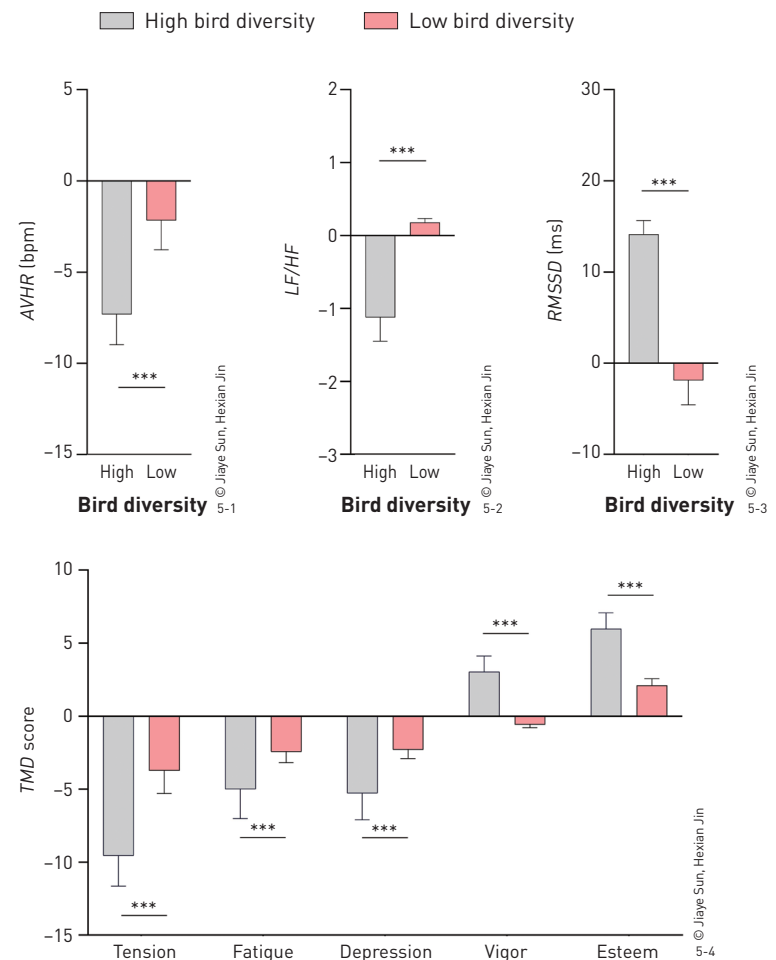


Fig. 5 The effect of bird diversity on physiological and psychological indicators.



RMSSD values (Fig. 5-3), resulting in a stronger arousal of negative emotions and a reduction in positive emotions. Low bird diversity also diminished feelings of esteem, indicating its dominant role in emotional regulation (Fig. 5-4).

3.2 Significant Synergistic Effects of Biodiversity Combinations on Physical and Mental Health Under Audio-Visual Interaction

Interaction analysis revealed a significant interaction effect between plant diversity and bird diversity on health benefits ($p < 0.05$), confirming that audio-visual biodiversity scenarios synergistically influence human physical and mental health. However, no significant interaction effects were found for *AVHR*, fatigue, or depression ($p > 0.05$). Therefore, further analysis focused only on *LF/HF*, *RMSSD*, and the three emotional factors of tension, esteem, and vigor, using simple effect analysis.

3.2.1 Plant Diversity as a Foundation for the Health Benefits of Bird Diversity

When plant diversity was at high or medium levels, high bird diversity significantly decreased *LF/HF* (Fig. 6-1) and increased *RMSSD* ($p < 0.001$) (Fig. 6-2). Concurrently, it alleviated tension (Fig. 6-3) and enhanced esteem and vigor ($p < 0.001$) (Figs. 6-4, 6-5).

When plant diversity was at a low level, high bird diversity still significantly reduced *LF/HF* values ($p < 0.001$) (Fig. 6-2), indicating that the audio-visual environment with low plant and

low bird diversity led to a significantly higher degree of negative emotional arousal compared with the environment with low plant but high bird diversity. However, the difference in *RMSSD* change between high and low bird diversity groups was not significant ($p > 0.05$) (Fig. 6-1). Both high and low bird diversity groups showed decreased vigor (Fig. 6-5), and the enhancing effect on esteem completely disappeared, with no significant difference between the groups ($p > 0.05$) (Figs. 6-4, 6-5). This suggests that in a low plant diversity visual environment, regardless of whether the auditory environment had high or low bird diversity, individuals' physiological stress was not significantly alleviated, and both esteem and vigor showed a decreasing trend, with no difference between high and low bird diversity groups.

3.2.2 Bird Diversity Enhances the Emotional Improvement Effects of High Plant Diversity

Regardless of the level of bird diversity, compared with low plant diversity, high plant diversity significantly decreased *LF/HF* (Fig. 7-1) and increased *RMSSD* ($p < 0.001$) (Fig. 7-2), indicating that high plant diversity can effectively alleviate physiological stress. Under high bird diversity, the alleviating effect of high plant diversity on tension (Fig. 7-3) and its enhancing effects on esteem and vigor were significantly greater than under low plant diversity ($p < 0.05$) (Figs. 7-4, 7-5). Under low bird diversity, the difference in reducing tension between medium and low plant diversity groups was highly significant ($p < 0.001$) (Fig. 7-3).

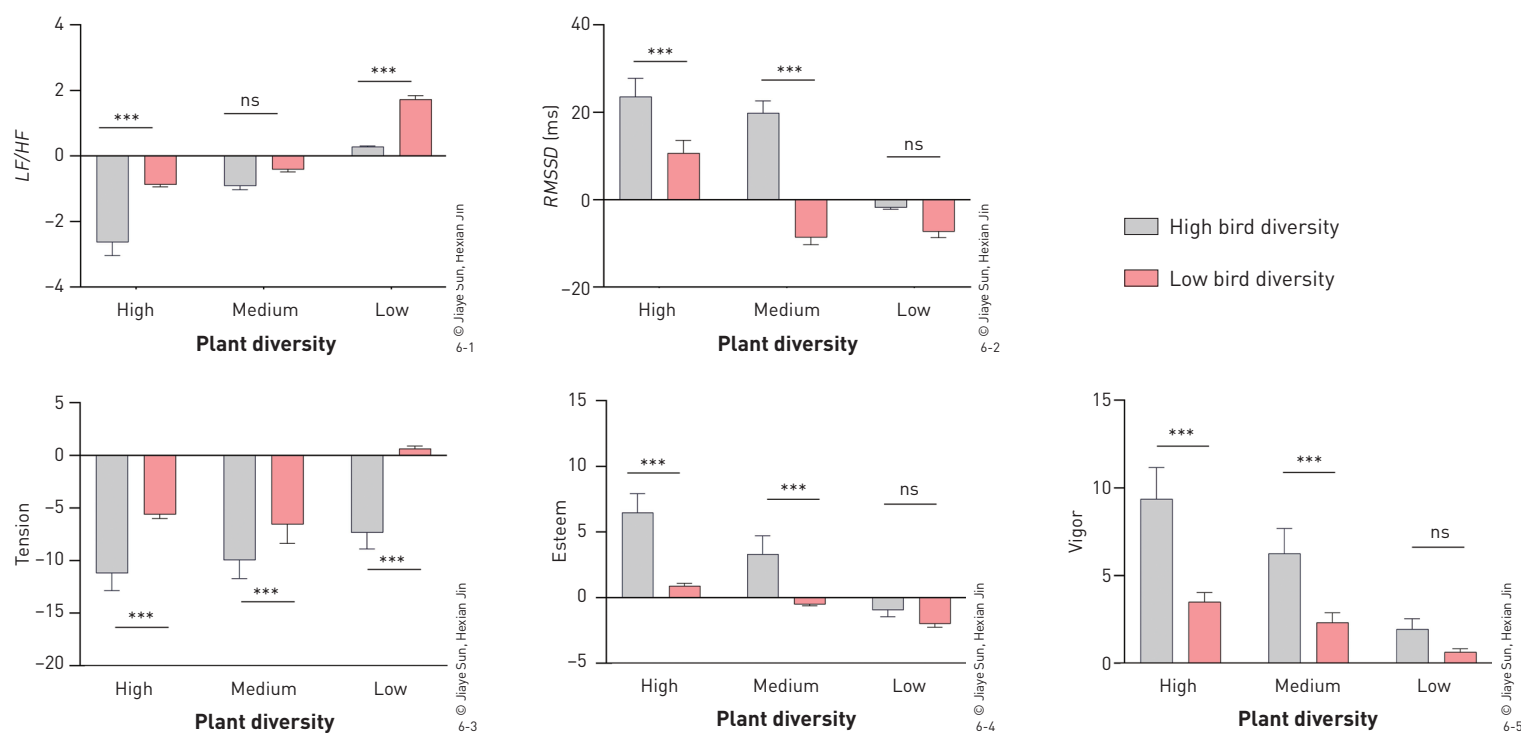


Fig. 6 The moderating effect of plant diversity on the health benefits of bird diversity.

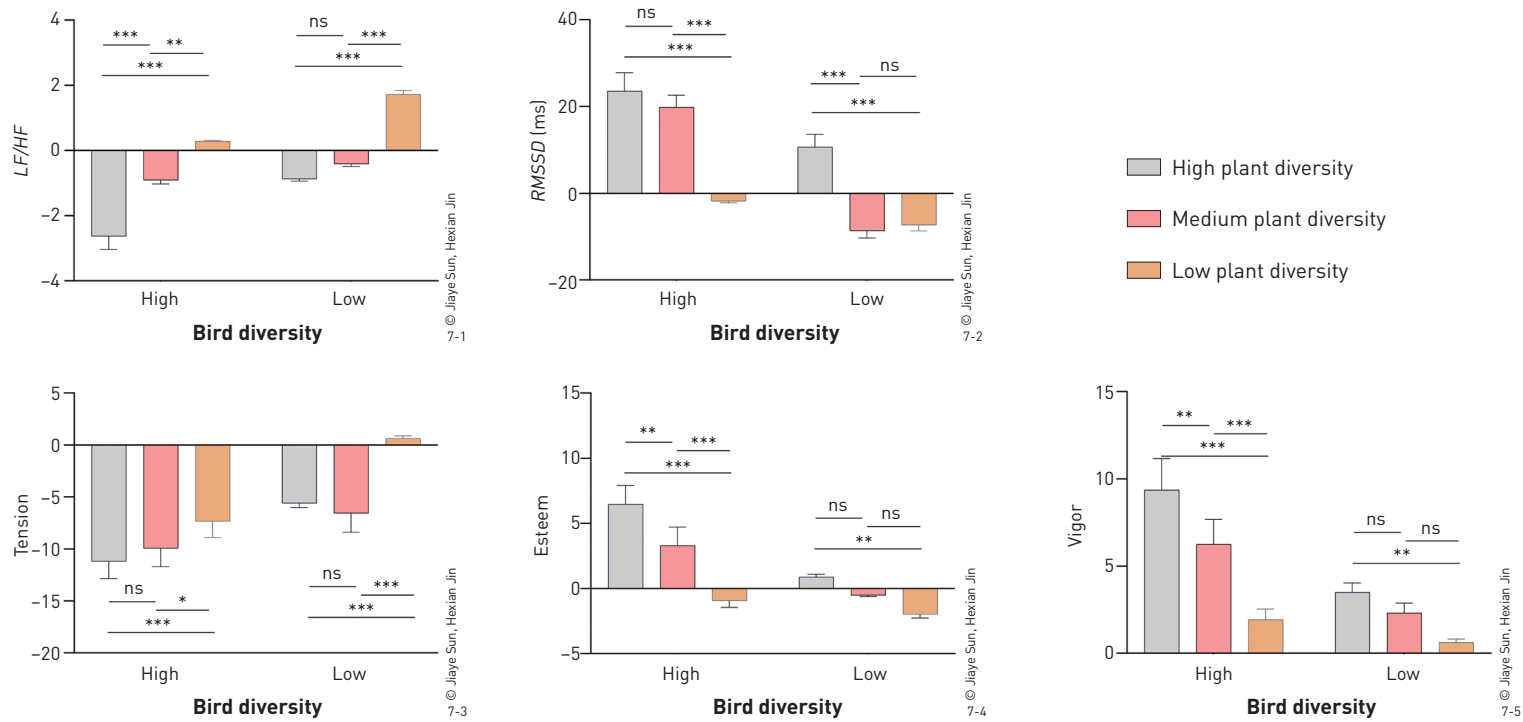


Fig. 7 The moderating effect of bird diversity on the health benefits of plant diversity.

3.3 Perceived Plant Diversity as the Primary Mediating Pathway in the Impact of Biodiversity on Mental Health

The study found that plant diversity and bird diversity were significantly positively correlated with perceived restorativeness and significantly negatively correlated with *TMD*. This indicates that both plant diversity and bird diversity can significantly enhance perceived restorativeness and significantly reduce total emotional disturbances. Plant diversity had a significant positive effect on

perceived plant diversity but no significant effect on perceived bird diversity. Bird diversity had a significant positive effect on both perceived bird diversity and perceived plant diversity. Perceived plant diversity had a significant positive effect on perceived restorativeness and a significant negative effect on *TMD*. Perceived bird diversity had a significant positive effect on perceived restorativeness but no significant effect on *TMD* (Table 3).

Based on the correlation analysis, a hypothesized mediation

Table 3: Correlation analysis among biodiversity, perceived biodiversity, and mental health benefits

Indicator	Plant diversity	Bird diversity	Perceived plant diversity	Perceived bird diversity	Perceived restorativeness	<i>TMD</i>
Plant diversity	1					
Bird diversity	0.022	1				
Perceived plant diversity	0.558***	0.177*	1			
Perceived bird diversity	0.169	0.822***	0.411***	1		
Perceived restorativeness	0.720***	0.402***	0.631***	0.480***	1	
<i>TMD</i>	-0.381***	-0.209*	-0.133*	-0.165	-0.212*	1

NOTE

* indicates $p < 0.05$, ** indicates $p < 0.01$, and *** indicates $p < 0.001$.

model (Fig. 8) was constructed, and a mediation effect analysis was conducted. The results indicate that the process by which biodiversity promotes psychological restoration is mediated by perceived biodiversity, primarily through perceived plant diversity. Plant diversity enhances individuals' perceived tree diversity, which in turn significantly increases the environment's Fascination and Extent, thereby improving mental health. Plant diversity also indirectly enhances vigor and esteem by increasing the perceived shrub diversity. Perceived herbaceous diversity significantly alleviates tension. The pathway of "bird diversity→perceived tree diversity→Fascination" demonstrated a full mediation, meaning that the positive effect of bird diversity on Fascination is entirely explained by the mediating variable of perceived tree

diversity. This suggests that bird diversity's role in enhancing the environment's Fascination is entirely dependent on its ability to enhance perceived plant diversity. Furthermore, bird diversity can enhance individuals' perceived plant diversity, thereby effectively alleviating tension, boosting esteem, and improving the evaluation of Extent of the environment (Table 4).

3.4 Individuals With Higher Nature Connectedness Obtain Greater Restorative Benefits in High Biodiversity Environments

The results showed that the health benefits of biodiversity were significantly influenced by individuals' nature connectedness. In plant diversity scenarios, the high nature connectedness group

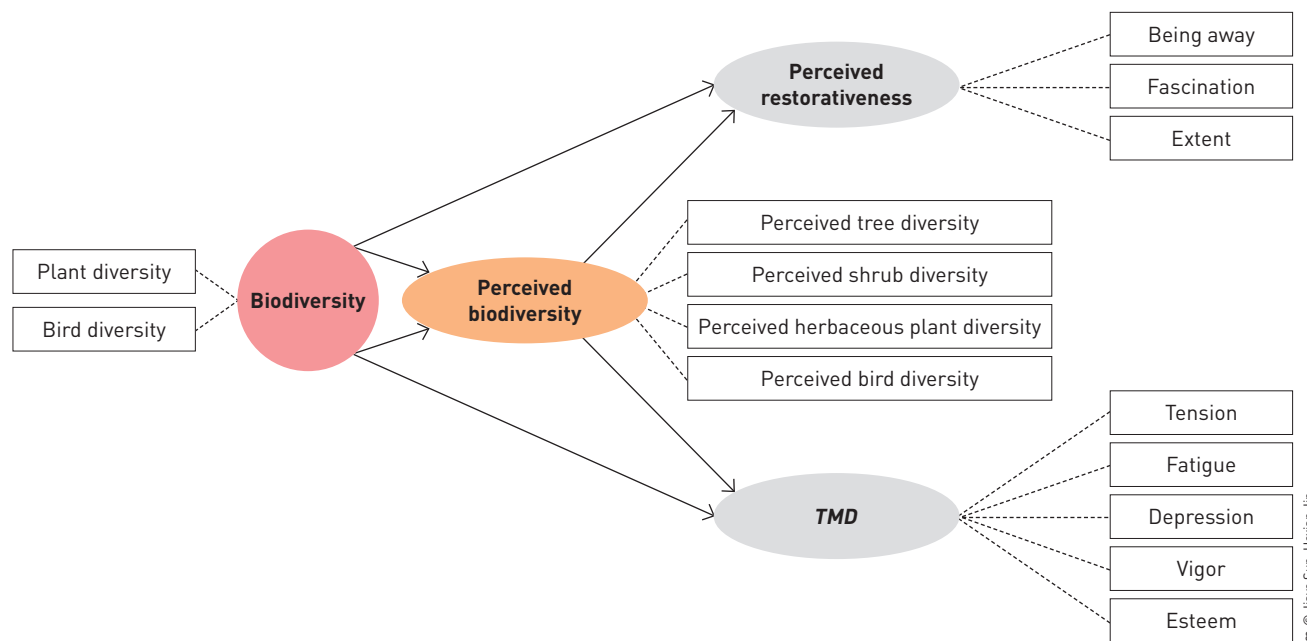


Fig. 8 The mediating effect model of perceived biodiversity between biodiversity and mental health.

Table 4: The mediating effects of perceived biodiversity on physiological and psychological indicators

Pathway	Effect	Unstandardized effect size	Standard error	95% Bootstrap Confidence Interval		Effect size	Test results
				Lower	Upper		
Bird diversity→perceived herb diversity→tension	Mediating Effect	-0.471*	0.079	-0.506	-0.421	8.305%	Partial mediation
	Direct effect	-5.200***	0.227	-6.002	-4.803	91.695%	
	Total effect	-5.671***	0.230	-6.133	-4.992	100.000%	
Plant diversity→perceived herb diversity→tension	Mediating effect	-1.536**	0.066	-1.986	-1.631	30.338%	Partial mediation
	Direct effect	-3.527***	0.290	-3.855	-3.184	69.662%	
	Total effect	-5.063***	0.301	-5.784	-4.521	100.000%	

(Continued)

Table 4: The mediating effects of perceived biodiversity on physiological and psychological indicators (Continued)

Pathway	Effect	Unstandardized effect size	Standard error	95% Bootstrap Confidence Interval		Effect size	Test results
				Lower	Upper		
Plant diversity→perceived shrub diversity→esteem	Mediating effect	1.410*	0.418	1.020	1.459	27.534%	Partial mediation
	Direct effect	3.711***	0.970	3.043	4.132	72.466%	
	Total effect	5.121***	0.839	5.057	5.371	100.000%	
Bird diversity→perceived shrub diversity→vigor	Mediating effect	0.444*	0.023	0.306	0.514	11.762%	Partial mediation
	Direct effect	3.331***	0.308	2.945	3.716	88.238%	
	Total effect	3.775***	0.400	3.102	4.190	100.000%	
Plant diversity→perceived shrub diversity→vigor	Mediating effect	1.719*	0.165	1.589	1.899	33.792%	Partial mediation
	Direct effect	3.368***	0.329	3.300	3.702	66.208%	
	Total effect	5.087***	0.421	4.964	5.205	100.000%	
Bird diversity→perceived tree diversity→fascination	Mediating effect	0.559*	0.036	0.395	0.716	14.720%	Pure mediation
	Direct effect	3.241	0.563	2.770	3.720	85.289%	
	Total effect	3.800***	0.530	3.482	3.929	100.000%	
Plant diversity→perceived tree diversity→fascination	Mediating effect	2.847**	0.065	2.227	2.883	27.561%	Partial mediation
	Direct effect	7.483***	0.726	7.389	8.020	72.439%	
	Total effect	10.330***	0.810	9.476	10.780	100.000%	
Bird diversity→perceived tree diversity→extent	Mediating effect	0.348	0.025	0.253	0.577	12.113%	Partial mediation
	Direct effect	2.525***	0.189	2.188	2.660	87.887%	
	Total effect	2.873***	0.187	2.400	3.901	100.000%	
Plant diversity→perceived tree diversity→extent	Mediating effect	1.770**	0.100	1.249	1.985	22.889%	Partial mediation
	Direct effect	5.963***	0.811	4.870	6.099	77.111%	
	Total effect	7.733***	0.703	6.633	7.981	100.000%	

NOTES

1. * indicates $p < 0.05$, ** indicates $p < 0.01$, and *** indicates $p < 0.001$.

2. The plant diversity group uses low plant diversity as the control group, and the bird diversity group uses low bird diversity as the control group.

was sensitive to high plant diversity ($p < 0.05$), but the difference in physiological restorativeness effects between groups was not significant in medium or low plant diversity environments ($p > 0.05$) (Figs. 9-1, 9-2). The pattern for the low nature connectedness group was the opposite. In bird diversity scenarios,

the high nature connectedness group showed significantly reduced physiological stress and diminished arousal of negative emotions under high bird diversity ($p < 0.05$), while there was no difference between the two groups under low bird diversity ($p > 0.05$) (Figs. 9-3, 9-4).

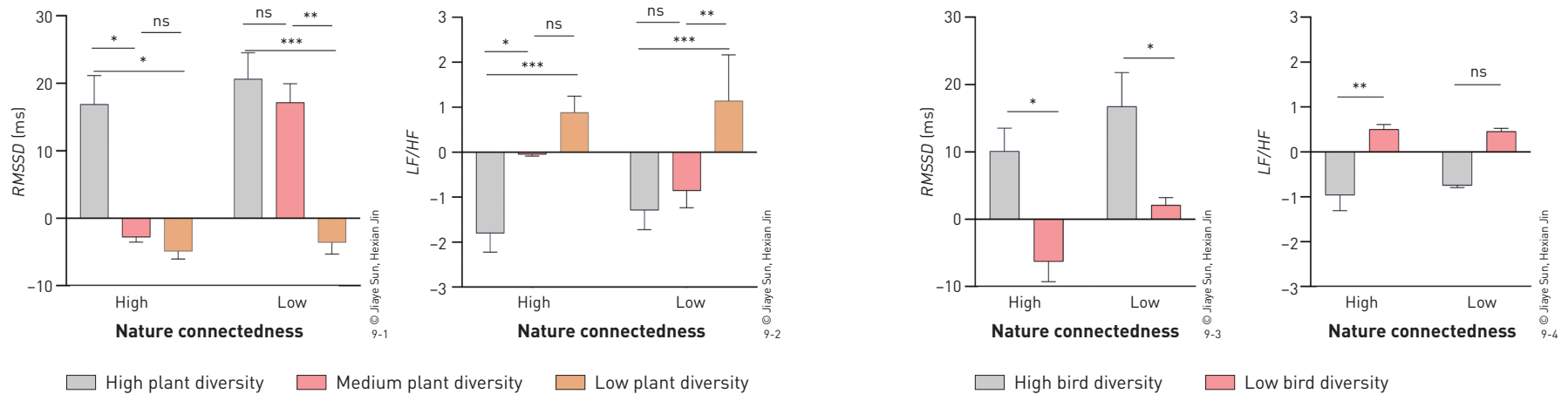


Fig. 9 The moderating effect of nature connectedness on the physiological restoration benefits of biodiversity.

4 Conclusions and Implications

4.1 Conclusions

The main findings of this study are as follows.

1) Rich plant and bird diversity in pocket parks have a significant positive impact on human health. Within a certain threshold, the health promoting effect becomes more pronounced as plant and bird diversity increase. High and medium plant diversity enhance autonomic nervous regulation and improve physiological stress, while low plant diversity induces physiological stress responses. Furthermore, both medium and low plant diversity have a relatively weak effect on improving depression. High bird diversity can reduce negative emotions, whereas low levels diminish positive emotions.

2) The combination of high plant diversity and high bird diversity under audio-visual interaction yields the greatest perceived restorative benefits. Plant diversity forms the foundation for restorative effects. In pocket parks with low plant diversity, pleasant bird sounds alone cannot enhance positive emotions. In auditory environments with high bird diversity, both high and medium plant diversity provide relatively high restorative benefits.

3) Perceived biodiversity act as a mediating variable influencing the health benefits of biodiversity on physical and mental well-being. Plant diversity can directly affect individual restoration outcomes and also influence mental health by affecting the perceived tree diversity, perceived shrub diversity, and perceived herbaceous plant diversity. The restorative benefits of bird diversity are mediated by the perceived tree diversity.

4) Individuals with higher nature connectedness are more sensitive to their environment and can obtain greater psychological

restorative benefits in environments with higher biodiversity. Individuals with high nature connectedness show relatively low restorative benefits in both medium and low plant diversity environments, whereas those with low nature connectedness show higher benefits in high and medium plant diversity environments. Low biodiversity environments provide no restorative benefits for any group.

This study employs VR technology to quantitatively and meticulously investigate the audio-visual biotic elements of pocket parks, demonstrating a degree of innovation. By exploring the physical and mental health benefits experienced by participants after exposure to different levels of plant and bird diversity, it enriches the literature on biodiversity as a natural factor in green space visual and soundscape research. Furthermore, this paper reveals the synergistic effects of biodiversity combinations on physical and mental restoration and the influence of the mediating pathway of perceived biodiversity on the health benefits of biodiversity, providing an important explanation for the unique formation of biodiversity's health promoting mechanisms. It also supplements the understanding of the benefit mechanisms for individuals with different levels of nature connectedness in biodiverse settings, offering a new basis for differentiated health interventions for diverse populations.

4.2 Enhancement Pathways for the Health Benefits of Biodiversity in Pocket Parks Based on Audio-Visual Interaction

The findings of this study provide a reference for improving plant and bird diversity in urban pocket parks, playing a significant

role in enhancing the capacity of green spaces to promote public health. Based on the conclusions above, it is recommended that the planning and design of pocket parks fully consider the integration of biodiversity creation with audio-visual perception to promote physical and mental health restoration.

1) Prioritize enhancing plant diversity, with a particular emphasis on designing for species richness in the tree layer. Increasing the variety of plant species in pocket parks^[49], especially by incorporating different types of trees, can not only directly improve emotions but also visually enhance perceived plant diversity, thereby indirectly amplifying the health benefits of bird diversity.

2) Actively create habitats suitable for birds, such as planting species that serve as food sources for birds to attract avian populations and increase their diversity (e.g., *Cinnamomum camphora*, *Celtis sinensis*, *Pyracantha fortuneana*)^[49-51], enhancing the perceptibility of the birdsong soundscape. Simultaneously, employing methods like planting noise blocking vegetation and adjusting vegetation layout and density can mitigate urban noise interference in bird habitats and reduce the masking effect of noise on birdsong^[39], thereby better realizing the restorative benefits of birdsong^[52].

3) Introduce designed birdsong soundscapes as an effective ecological compensation measure in situations where plant quantity is sufficient but species richness is limited. The strategic use of soundscape systems to broadcast birdsong can directly elevate the level of perceived bird diversity by the public, subsequently enhancing health restoration benefits.

4) Adopt differentiated intervention and design strategies for groups with varying levels of nature connectedness. For groups with high nature connectedness, increasing on-site species diversity can help achieve maximum restorative benefits. For groups with low nature connectedness, strategies involving nature cognition interventions, such as using soundscape QR codes and organizing bird call identification activities, should be implemented. These can improve their ecological knowledge and sensitivity to perceived biodiversity, helping them benefit from high biodiversity environments^[19,25].

4.3 Limitations and Prospects

This study has certain limitations. First, regarding the research subject, the biodiversity of a pocket park is complex. This study focused only on plant diversity and bird diversity to investigate the relationship between biodiversity and human health benefits. Future research could explore the effects of native plant diversity,

insect diversity, etc. on human physical and mental health. Studies could also investigate the restorative benefits of other biodiversity features from the perspective of multi-sensory perception, such as color diversity, sound diversity, and olfactory diversity. Second, research could further explore the differences in the health benefits of biodiversity across varied types and sizes of pocket parks. Third, this study examined the restorative benefits of biodiversity only in an idealized virtual green environment. Future studies could control for other variables to investigate the impact of different levels of biodiversity on environmental restorative benefits within the context of real surrounding environments. Finally, the experimental participants in this study were all university students. Future research should innovate in terms of subject groups, seeking to understand the differences in the perceived restorative benefits of biodiversity among people of different age groups and varying educational backgrounds.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at <https://doi.org/10.15302/J-LAF-2026-0030>.

Competing interests | The authors declare that they have no competing interests.

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口袋公园生物多样性感知对人体健康恢复效益的影响

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摘要

城市绿地中多样的生物因子既是构成环境适应的基础条件, 又能为人类带来健康益处。然而, 鲜有研究从视听交互感知维度探讨口袋公园这一绿地类型中生物多样性的健康效益。本研究选取生物多样性中的植物多样性(高、中、低)作为视觉自变量, 鸟类多样性(高、低)作为听觉自变量, 设置6种口袋公园生物多样性虚拟场景。共招募60名受试者, 每位受试者随机体验2种生物多样性场景, 通过心电(HRV)及情绪状态量表(POMS)、感知恢复量表(PRS)、生物多样性感知量表(PBS)分析口袋公园中不同类型和水平的生物多样性恢复效益。研究表明: 1) 丰富的植物和鸟类多样性对人体健康具有显著正向影响。2) 高植物多样性和高鸟类多样性视听交互感知下的恢复效益最佳。3) 生物多样性感知作为中介变量影响生物多样性对身心的健康效益。4) 自然联结度越高的个体在生物多样性越高的环境中可以获得更大的恢复性效益。因此, 在口袋公园优化设计时, 应考虑提升植物与鸟类多样性、营造适宜生境、引入声景补偿和差异化干预策略, 以发挥绿地的健康促进效益。本研究为改善城市口袋公园的植物多样性和鸟类多样性环境提供了参考, 对增强城市绿地的公众健康促进效应具有重要意义。

关键词

生物多样性; 城市绿色空间; 视听交互; 口袋公园; 人类健康; 植物多样性; 鸟类多样性

文章亮点

- 证实了高植物多样性与高鸟类多样性组合对身心恢复的协同增效作用
- 揭示了生物多样性通过植物多样性感知影响健康的中介机制
- 为不同自然联结度群体的健康干预提供了新依据
- 为口袋公园生物多样性视听环境设计提供了科学支持

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