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Effects of Outdoor Informal Learning Space Typologies on Cognition and Emotional Regulation: A Multimodal Psychophysiological Analysis of College Students' Self-study Activities

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KEYWORDS

Informal Learning Environments;
Self-Study;
Electroencephalography;
Heart Rate Variability;
Attention Restoration

ABSTRACT

Informal learning spaces are increasingly seen as vital for self-study, prompting research on how environmental features affect learning efficiency and well-being. This randomized controlled experiment examined three outdoor settings—waterfront, woodland, and semi-open plaza—by having 81 undergraduates complete 5-minute self-study tasks in each, with simultaneous electroencephalography (EEG) and heart rate variability (HRV) monitoring. Cognitive tasks, psychological scales, and environmental preference inventories were used to assess changes in learning states. Results showed significant differences across environments in physiological, cognitive, and psychological responses. Compared to plazas, waterfront and woodland settings produced more favorable outcomes, as indicated by EEG, HRV, attention, and emotion metrics. Cluster analysis revealed structured, synergistic relationships among indicators. Findings support the value of nature-based environments, especially waterscapes and woodlands, in enhancing physiological regulation and attentional restoration, providing empirical evidence for health-oriented design of campus informal learning spaces.

INTRODUCTION

In university campuses, informal learning activities, as extensions of classroom instruction, are receiving growing attention from educational researchers and administrators. Compared to formal classroom settings, students increasingly prefer informal learning spaces, such as libraries, study rooms, and outdoor areas, for self-study and knowledge acquisition during their free time (Ramu, Taib, and Massoomeh 2021). These spaces, valued for their flexibility, comfort, and social accessibility, serve as critical spatial facilitators for self-study (Wu et al. 2021). Informal learning spaces not only expand the functional boundaries of educational environments but also reflect higher education's emphasis on learner autonomy, environmental adaptability, and individual differences, demonstrating sustainable resilience in spatial design. However, different types of informal

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learning spaces (e.g., indoor study areas vs. natural environments) may differ in the extent to which they support cognition and emotion, warranting further investigation into their psychophysiological impacts on learners.

Emerging research has begun exploring how learning environments influence university students' mental and physical states. Prolonged sedentary study in indoor spaces (e.g., classrooms and study halls) has been linked to mental fatigue and reduced cognitive efficiency (Friedenreich et al. 2019; Hallgren et al. 2020). In contrast, natural environments have demonstrated consistent benefits for attention restoration, emotional regulation, and stress reduction across populations, enhancing cognitive performance (Stenfors et al. 2019). Moderate outdoor activity, in particular, has been identified as a key pathway to cognitive recovery and mood enhancement (Ma et al. 2024), suggesting the potential of natural settings in supporting learning processes.

The mechanisms underlying these benefits likely involve both sensory restoration effects and individual differences in learning styles, focus strategies, and spatial behaviors (Wang and Han 2021; Wu et al. 2021). These factors collectively shape cognitive and emotional responses across various types of informal learning spaces. In real-world campus contexts, students dynamically choose between libraries, study rooms, and outdoor green spaces based on concentration needs, social preferences, or comfort, a behavioral pattern that underscores the practical value of natural environments in supporting autonomous learning and psychological well-being.

Recent interdisciplinary research has examined informal learning spaces through lenses of landscape planning and educational psychology, exploring user preferences and functional efficacy (Harris, Birdwell, and Basdogan 2024; Anggiani and Heryanto 2018). Pilot initiatives like nature-based curricula report improved classroom engagement and mood after brief natural exposure (Kuo, Browning, and Penner 2018). However, most studies focus on short-term outcomes (e.g., mood or classroom performance), leaving open the question of how well such environments support complex and sustained learning tasks. While evidence supports nature's role in attention and cognition (Koivisto et al. 2024), existing work tends to prioritize transient exposures (e.g., window views or brief walks) over sustained, ecologically valid learning scenarios.

Notably, many students favor semi-open spaces near libraries for self-study over enclosed rooms, a preference driven by comfort, perceived safety, ventilation, and the avoidance of physical confinement (von Sommoggy et al. 2020). This behavior underscores the dynamic interplay between learning needs and environmental features.

These observations suggest that campus landscapes may modulate both spatial choices and learning efficiency, yet the underlying psychobehavioral mechanisms remain understudied. To address this gap, we conducted a field experiment comparing three natural campus environments (waterfront, woodland, and semi-open plaza) during high-cognitive-load self-study tasks. Multimodal data, including EEG, HRV, cognitive task performance, and psychological scales, were analyzed to assess learning-state dynamics and identify nature's regulatory pathways. Our findings aim to advance evidence-based strategies for green campus design, informal space optimization, and mental health promotion, offering actionable insights for sustainable learning environments.

METHODS

Site Observation and Selection

To identify representative natural learning environments on campus, our research team conducted a week-long field observation from March 3 to March 9, 2025. During this period, we systematically recorded students' lengths of stay, activity types, and frequency of use in various open spaces to determine preferred locations for informal learning. Based on observational data, we selected three distinct open spaces near the library of Southwest University of Science and Technology as experimental sites: a waterfront environment, a woodland environment, and a semi-open plaza environment (**Figure 1**).

The three experimental environments were comparable in accessibility but exhibited notable differences in landscape composition. The semi-open plaza environment featured an unobstructed layout with minimal vegetation coverage. The woodland environment was dominated by trees and grassy areas, with a canopy density of approximately 0.8. The waterfront environment was situated along the lakeshore south of the library, encompassing a water surface area of about 11,000 m^2. These locations were frequently used by students for self-study activities, often with portable seating.

Formal data collection was carried out from March 23 to March 27, 2025, during periods of stable weather conditions characterized by light winds ($\leq$ 2 m/s), no precipitation, and an average daily temperature of 23°C, which conditions considered ideal for outdoor experimentation. To control for environmental variables, all experimental sessions were scheduled during consistent time windows (9:00-11:00 AM and 2:00-4:00 PM), avoiding peak usage hours to ensure procedural consistency and comparability across sites.

Participants

We recruited 95 undergraduate volunteers for this study. All participants met the following inclusion criteria: **1)** no history of psychiatric disorders or current smoking habit, **2)** normal or corrected-to-normal visual acuity, and **3)** body mass index (BMI) within the normal range (18.5-23.9 kg/m^2). Twelve participants withdrew during the study period due to personal reasons. To maintain balanced sample sizes, we randomly selected 81 participants (39 male, 42 females; mean age = 21.04 ± 1.97 years) from the remaining pool to complete all experimental procedures. Prior to participation, all subjects received detailed explanations of the experimental protocol and provided written informed consent in accordance with ethical standards.

Figure 1 | Study sites

A) Satellite image of the study site. The black, green, and blue circles indicate the locations of the plaza environment, the waterfront environment, and the woodland environment, respectively. Panels B) to D) show the real-world scenes of the **B)** plaza, **C)** woodland, and **D)** waterfront environments.

Physiological Measures

Physiological states were assessed through electroencephalogram (EEG) and heart rate variability (HRV). EEG signals were collected using an Emotiv EPOC device with 8 channels (AF3, AF4, F3, F4, P7, P8, O1, O2) covering prefrontal, temporal and occipital regions primarily associated with cognitive control and perceptual processing. The EEG data sampling rate was set at 128 Hz with a bandpass filter of 0.2-45 Hz. HRV data were recorded using Polar H10 chest straps, including standard deviation of NN intervals (SDNN) and low frequency/high frequency power ratio (LF/HF ratio) to evaluate time-domain and frequency-domain aspects of autonomic nervous system activity.

Cognitive Performance

Participants' cognitive performance was assessed using the Digit Span Task and a simplified Stroop test. The Digit Span Task measured working memory capacity. At the beginning of the test, a random sequence of 3 digits was displayed on screen, with each digit shown for 1 second at 1-second intervals. Participants needed to input the digits in order. Based on response accuracy, the length of the subsequent sequence increased or decreased by one digit. Termination criteria included either two consecutive incorrect responses or a total test duration of 300 seconds. Metrics recorded included the maximum correct digit span and the overall accuracy rate.

The Stroop test evaluated attentional selectivity and inhibitory control. The test consisted of two conditions: congruent and incongruent color conditions. Participants needed to identify the semantic meaning of presented words (rather than the font color) and make response judgments. The test used five Chinese color words (red, green, blue, yellow, black) presented in matching or mismatching colors, with 10 trials for per condition.

Average reaction time for each condition was recorded, and the time difference between incongruent and congruent conditions was calculated as the Stroop interference effect. Both tasks were implemented using a custom program developed by the researchers (see supplementary materials) to automatically record reaction times and accuracy rates, minimizing measurement errors from manual timing.

Psychological States

Participants' psychological states were evaluated using the Chinese version of the Profile of Mood States (POMS) and an environmental preference scale. The Chinese POMS contains 40 items rated on a 5-point Likert scale from 1(not at all) to 5 (extremely). Items were categorized into six mood dimensions: tension, depression, anger, vigor, fatigue, and confusion.

Total Mood Disturbance (TMD) scores were calculated by summing the negative mood subscales and subtracting the vigor score, thereby reflecting overall emotional state. The environmental preference scale used a 7-point Likert rating from 1 (strongly dislike) to 7 (strongly like) to assess participants' overall preference for the three experimental environments (waterfront, woodland, and open plaza). The questionnaire was

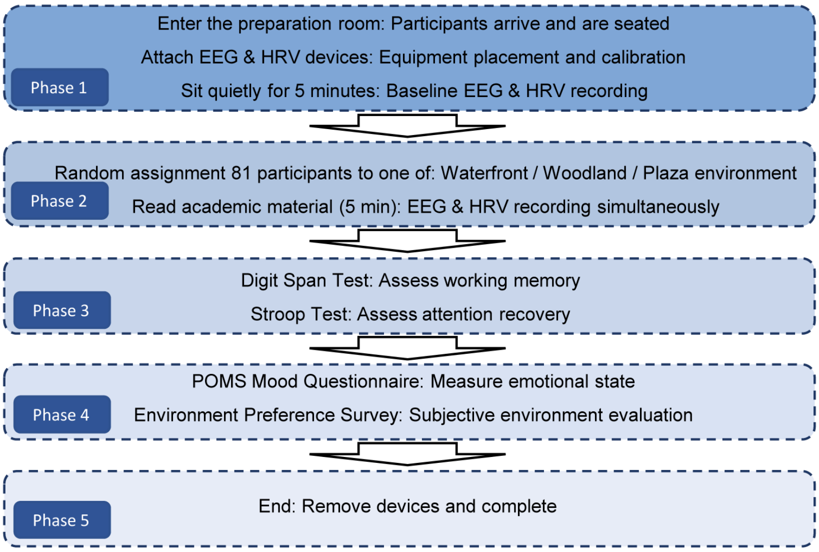

Figure 2 I The study procedure diagram

administered immediately after the task to capture immediate environmental impressions.

Procedure

The experimental procedure consisted of four stages (**Figure 2**). First, during the baseline period, participants entered the preparation room, donned EEG and HRV monitoring equipment, and after signal calibration, sat quietly for 5 minutes to record baseline physiological states. Next, in the cognitive load task stage, participants were randomly and equally assigned to one of the three experimental environments (waterfront, woodland, or open plaza). After sitting quietly in the target environment for 5 minutes, they began reading assigned academic materials and memorizing key points while EEG and HRV data were synchronously recorded to simulate high cognitive load in real learning situations. Then, in the testing stage, participants first completed the Digit Span Task to assess working memory performance, followed by the simplified Stroop test to measure attention recovery effects. Finally, all participants completed the POMS and environmental preference questionnaires to collect subjective psychological and attitudinal data. Throughout the procedure, participants were prohibited from using electronic devices other than those required for the study, and interaction between participants was not allowed to minimize experimental interference. Each experimental session was separated by at least 24 hours to reduce potential learning effects from repeated exposure.

Data Analysis

All data were statistically processed using SPSS 27 software. First, one-way ANOVA was used to compare overall differences in psychological, physiological and cognitive indicators after exposure to the three environments. For results showing significance ($p < 0.05$), Tukey HSD post hoc test were conducted. Pearson correlation analysis was used to examine relationships between indicators. Subsequently, variables were standardized using Z-scores, and hierarchical cluster analysis was performed using Euclidean distance as the similarity measure combined with Ward's minimum variance method. This analysis was used to explore clustering structures and potential interrelationships among multimodal indicators. All statistical tests were two-tailed with significance level set at $\alpha = 0.05$.

RESULTS

Neurophysiological Measurement Results

The EEG spectral power analysis (Figure 3) revealed significant effects of different environments on the β/α index at multiple electrode sites except O1. Specifically, the prefrontal regions (AF3, AF4, F3, F4) exhibited the most pronounced differences across environments, with the semi-open plaza environment showing significantly higher β/α indices than both the woodland and waterfront environments ($p < 0.05$). The woodland environment had significantly lower β/α indices than the waterfront environment ($p < 0.05$). In the parietal regions (P7, P8), the β/α index was significantly lower in the semi-open plaza environment compared to the waterfront and woodland environments ($p < 0.05$), but no significant difference was observed between the waterfront and woodland environments ($p > 0.05$). For the occipital regions (O1, O2), except for the O2 channel in the waterfront environment, which showed a significantly lower β/α index than the semi-open plaza environment ($p < 0.05$), no significant differences were found in the remaining pairwise comparisons.

Heart Rate Variability Indicators

The results of heart rate variability (HRV) are shown in **Figure 4**. The waterfront environment showed significantly higher SDNN, RMSSD, and pNN50 values compared to the semi-open plaza environment ($p < 0.05$), along with significantly lower LF/HF ratio ($p < 0.05$). The woodland environment also demonstrated significantly

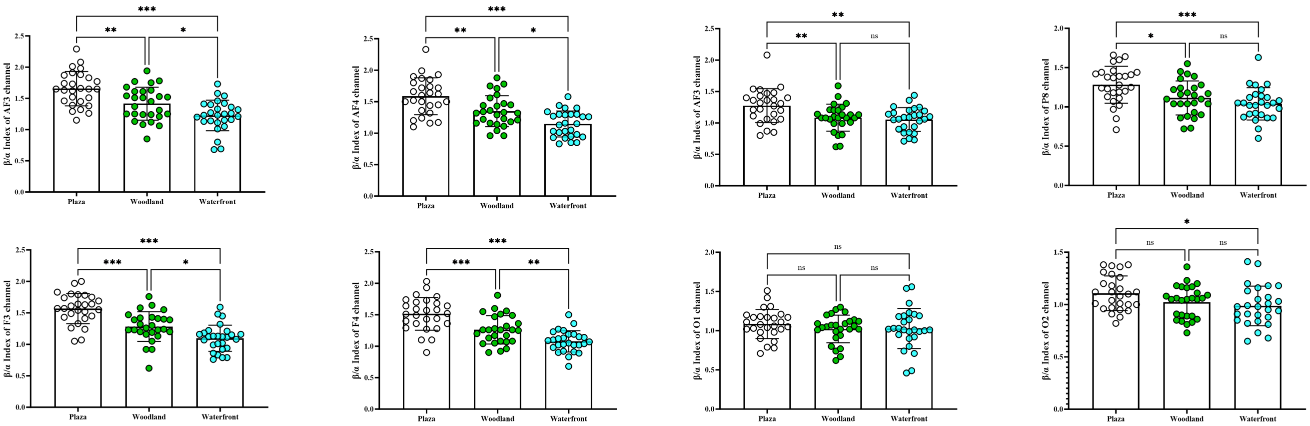

Figure 3 | The β/α index of the eight electroencephalogram (EEG) signal channels

* $p < 0.05$, ** $p < 0.01$, ns $p > 0.05$.

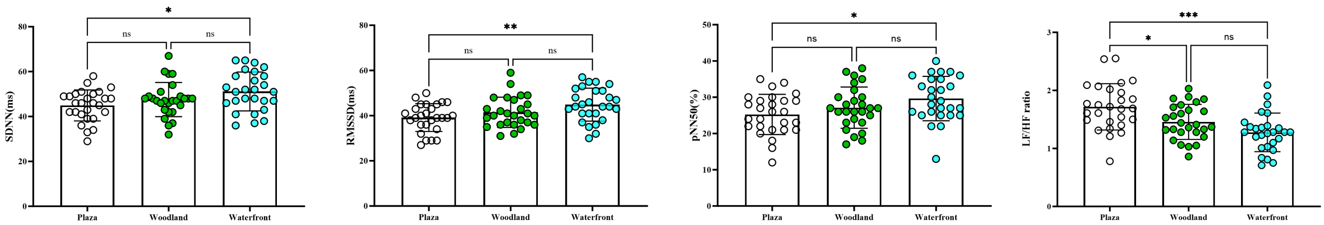

Figure 4 | Analysis results of heart rate variability

lower LF/HF ratio than the semi-open plaza environment ($p < 0.05$).

Cognitive Behavioral Performance Results

As shown in Figure 5, in the Digit Span Task, both the maximum correct digit span and overall accuracy rate were significantly higher in the waterfront environment compared to the semi-open plaza environment ($p < 0.05$), while no significant differences were found between the woodland environment and either the semi-open plaza or waterfront environments ($p > 0.05$). The Stroop test results (**Figure 6**) showed no significant differences in reaction times between congruent and incongruent conditions across the three environments ($p > 0.05$). However, the interference effect difference was significantly lower in the waterfront environment compared to the semi-open plaza environment ($p < 0.05$), but showed no significant difference when compared to the woodland environment.

Psychological State and Environmental Preference Results

The total mood disturbance (TMD) scores from POMS and environmental preference ratings are shown in **Figure 7**. The semi-open plaza environment showed significantly higher TMD scores compared to both the woodland and waterfront environments ($p < 0.05$), while no significant difference was found between the latter two. For environmental preference ratings, the semi-open plaza environment received significantly lower scores than both the woodland and waterfront environments ($p < 0.05$), with the woodland environment also scoring significantly lower than the waterfront environment.

Correlation and Cluster Analysis Results

Figure 8 presents the Pearson correlation coefficients and cluster analysis results among various psychological, physiological, and cognitive indicators. Several significant correlations were observed between different types of variables. First, among heart rate variability (HRV) indicators, SDNN, RMSSD and pNN50 showed strong positive correlations with each other, particularly between RMSSD and pNN50 ($r = 0.94$), indicating consistent variation patterns among these measures. Second, Stroop Congruent Time and Stroop Incongruent Time demonstrated high correlation ($r = 0.95$), suggesting similar time consumption patterns between the two task conditions. Additionally, Total Mood Disturbance (TMD) scores showed moderate positive correlations with β/α ratios from multiple EEG channels (AF3, AF4, F3, F4; $r = 0.40$-0.51), implying associations between mood states and prefrontal cortical activity. Regarding cognitive performance, Maximum Correct Digit Span and Total Correct Digit Span were significantly positively correlated ($r = 0.58$), reflecting their commonality in assessing working memory capacity. Meanwhile, environmental preference scores showed negative correlations with several HRV indicators (RMSSD, pNN50), possibly suggesting relationships between subjective

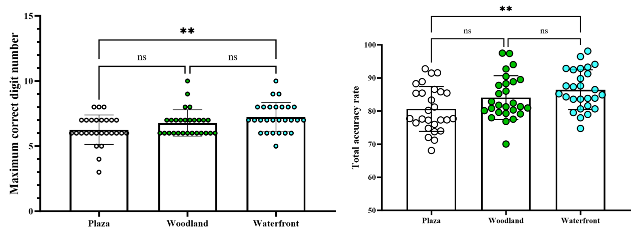

Figure 5 | The results of the digit span test

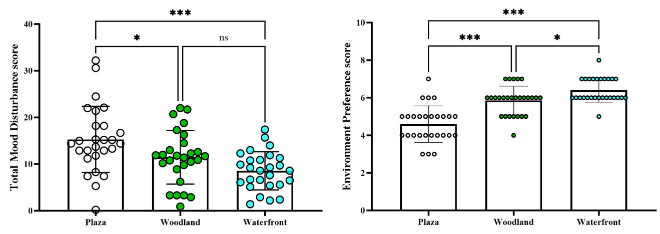

Figure 7 | The total mood disturbance score and the environment preference score

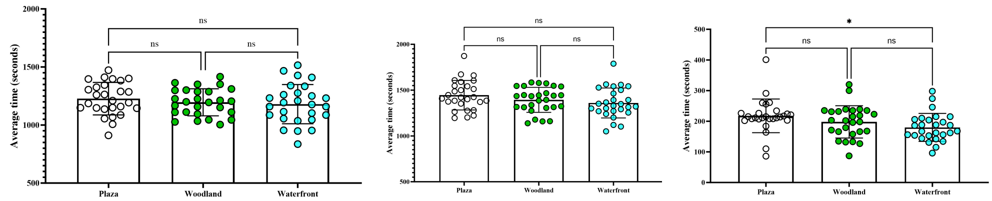

Figure 6 | The results of the Stroop test

environmental preferences and autonomic nervous system activity.

In hierarchical cluster analysis, variables were automatically grouped into several characteristic clusters based on correlation structures. Overall, HRV indicators (SDNN, RMSSD, pNN50, LF/HF) formed one major cluster, demonstrating their physiological consistency. Stroop-related variables (Congruent Time, Incongruent Time, Time Difference) were grouped into the same cluster branch, indicating close relationships among these reaction time parameters. EEG β/α ratios showed spatial clustering patterns with prefrontal channels (AF3, AF4, F3, F4) and parieto-occipital channels (P7, P8, O1, O2) forming separate subclusters, reflecting regional activity characteristics. Furthermore, TMD scores clustered with prefrontal EEG channels, further supporting the close relationship between mood states and prefrontal EEG activity. Digit Span task indicators formed an independent small cluster, demonstrating the uniqueness of this cognitive assessment. The overall clustering structure revealed potential functional relationships and grouping characteristics among multidimensional physiological, psychological and cognitive indicators.

DISCUSSION

Differential Effects of Outdoor Environment Types on Cognitive Efficiency and Emotional Regulation

This randomized controlled field study systematically compared the effects of three typical outdoor environments - waterfront, woodland, and open non-landscaped areas - on cognitive performance, emotional states, and physiological indicators during college students' self-study. The results demonstrate that natural landscape environments, particularly waterfront and wooded areas, significantly enhanced attentional control and working memory performance compared to non-landscaped open spaces. These findings, based on behavioral measures including Stroop test and Digit Span Task, complement previous research perspectives focusing on emotional regulation or EEG characteristics (Xu et al. 2024; Maryam et al. 2017).

The study design emphasized the authenticity and functionality of the learning task itself. Unlike previous studies that examined nature exposure in rest or emotional recovery contexts (Oh, Kim, and Park 2019; Zhao et al. 2025), this research for the first time embedded self-study tasks within experimental settings, focusing on changes in actual learning efficiency. This task-oriented design better approximates college students' daily learning situations and helps address the lack of behavioral measurement dimensions in natural environment intervention research (Christoph et al. 2017; Gifford and Robert 2014). Notably, the changes in emotional states and cognitive performance outcomes were not entirely consistent, providing valuable supplementary evidence to the traditional view that positive emotions necessarily lead to efficient cognition (A. Rodríguez-Muoz et al. 2021).

Simultaneously, heart rate variability (HRV) results revealed differences in physiological regulatory mechanisms across environment types. The waterfront environment significantly outperformed open spaces in parasympathetic activity indicators (SDNN, RMSSD, and pNN50), with significantly lower LF/HF ratios, suggesting its advantages in alleviating physiological stress and enhancing mind-body stability. The woodland environment also demonstrated certain effects on LF/HF regulation. These results not only validate the physiological efficacy of natural environments in emotional regulation but also expand the application of HRV as an objective indicator in educational settings (Gifford and Robert 2014; Maryam et al. 2017), further supporting the theoretical framework of psychological-physiologi-

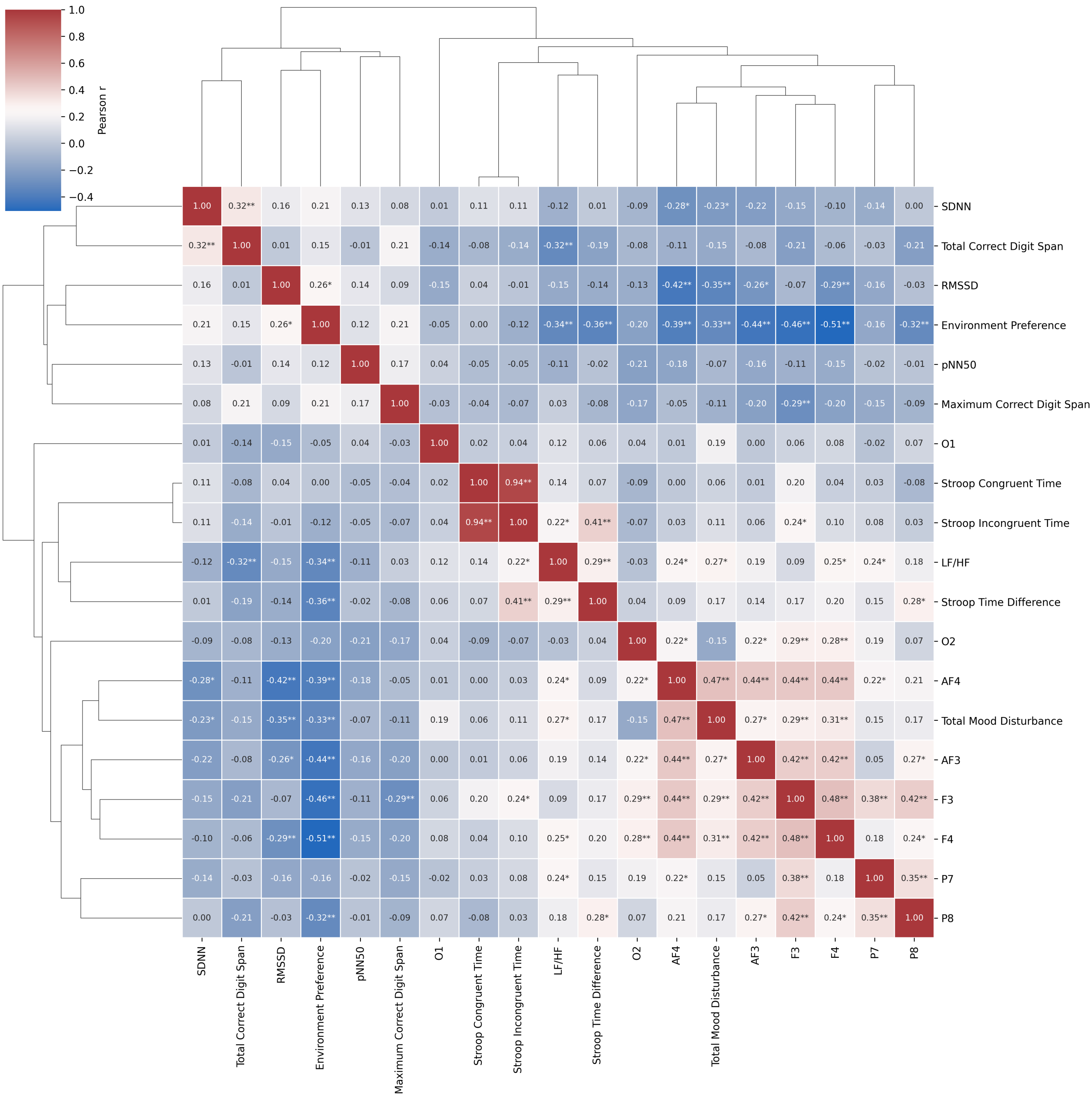

Figure 8 | The clustering heat map

cal-cognitive linkage (Oh, Kim, and Park 2019; Zhao et al. 2025).

Expanding Research Pathways for Natural Environment Interventions in Learning Contexts

Recent years have seen growing research on the effects of natural environments on psychological and cognitive performance, yet most studies focus on short-term emotional responses or attention restoration after nature exposure (Kuo, Browning, and Penner 2018; Koivisto et al. 2024), with limited empirical exploration integrating natural environments with authentic learning tasks. By introducing structured self-study tasks and implementing environmental interventions in real college learning contexts, this study directly quantified the regulatory effects of three typical outdoor natural environments on cognitive function using Stroop tests and Digit Span Tasks as core measurement tools, thereby addressing gaps in ecological validity and behavioral measurement in existing research (Christoph et al. 2017; Harris, Birdwell, and Basdogan 2024).

Unlike previous studies emphasizing emotional regulation, this research expanded measurement dimensions by constructing a multimodal assessment system encompassing subjective psychological scales, objective cognitive performance, and HRV physiological indicators, a psychological-behavioral-physiological tripartite framework (Barrett et al. 2017; Gifford and Robert 2014). This design aligns with the multimodal integration perspective proposed by Beute and de Kort (2018), marking its first systematic application in learning contexts to reveal pathways through which natural environments optimize learning states via mind-body coupling mechanisms.

While HRV has been used to assess emotional recovery effects during nature exposure (Ma et al. 2024), this study pioneered its synchronous collection during learning tasks combined with classic cognitive tests like Stroop, demonstrating waterfront environments' significant effects in enhancing parasympathetic activation indicators (SDNN, RMSSD) and reducing LF/HF ratios. These results provide quantitative evidence for the physiological basis of natural environment interventions in supporting learning efficiency.

In environmental classification, this study moved beyond the binary natural/non-natural contrast framework by selecting waterfront, woodland, and open plaza environments based on actual campus spatial structures, highlighting heterogeneous effects of natural element combinations and spatial organization on learning support (Wang and Han 2021; Mateo-Canedo et al. 2023). Results showed waterfront environments' superior performance in both cognitive enhancement and physiological regulation, suggesting aquatic landscapes may possess regulatory potential beyond ordinary green spaces. This finding provides theoretical support for transforming campus green spaces into cognition-friendly ecological campuses (Hallgren et al. 2020).

Practical Implications of Natural Learning Environment Research for Campus and Urban Space Design

The experimental results of this study demonstrate significant differences in the effects of various types of campus natural landscape environments on the learning efficiency and psycho-physiological states of university students during self-study, with waterfront environments exhibiting the most superior performance. These findings provide practical insights for campus and urban space planning in three key areas: functional optimization of informal learning spaces, systematic transformation pathways for green campuses, and the expansion of educational functions in urban public spaces.

First, greater emphasis should be placed on the functional design of landscape features in informal learning spaces. Currently, many university outdoor spaces primarily serve aesthetic or circulation purposes, with insufficient consideration given to learning behaviors and usage patterns. This study reveals that students frequently engage in self-study activities in areas such as tree groves, lakesides, and pathways. Equipping these spaces with learning-friendly infrastructure, such as sunshades, optimized natural lighting, and seating with power outlets, could significantly enhance space utilization and learning efficiency (Mateo-Canedo et al. 2023). This perspective aligns closely with the expectation-perception-behavior framework proposed by Guo and Sui (2025), which highlights the positive impact of environmental elements (e.g., blue tones, wooden textures) on learning efficiency, as well as the critical role of spatial accessibility and acoustic quality in optimizing learning experiences. Therefore, green campus development should prioritize multisensory regulation strategies that align with user behavior patterns.

Second, campus master planning should promote landscape space reorganization based on the differential efficacy of environmental types. This study found that waterfront environments significantly outperformed woodland and open plaza spaces in terms of HRV indicators and cognitive task performance, suggesting that water features, acoustic conditions, and spatial enclosure may be key factors in supporting learning (Hallgren et al. 2020). Universities can prioritize the preservation or redesign of spatially distinctive nodes, such as waterfront edges, tree groves, and low-noise zones, during campus renewal projects. By integrating appropriately sheltered spatial arrangements, these areas can be transformed into functional learning spaces that differ from traditional recreational landscapes.

Lastly, the findings of this study can also be extended to the planning and educational function integration of urban public spaces. Even in non-campus settings, urban courtyards, linear greenways, and small pocket parks can be optimized through design to serve as urban learning patches that support informal learning for adolescents and residents. This strategy contributes to the equitable spatial distribution of educational resources, fosters the coupling of urban communities and learning-oriented societies, and aligns with the United Nations Sustainable Development Goals (United Nations 2023), particularly those related to healthy cities, quality education, and sustainable communities. For adolescent populations in particular, high quality, learning friendly outdoor spaces have the potential to enhance learning autonomy, emotional restoration, and behavioral motivation, thereby advancing user demand-driven, health-oriented urban design principles in the field of education.

Limitations and Future Directions

This study has several limitations. First, the sample size was relatively small, and all participants were recruited from the same college, resulting in a homogeneous academic background that may limit the generalizability of the findings. Second, although the experimental tasks were designed to simulate real-world learning scenarios, the short duration of the study makes it difficult to assess the long-term effects of environmental interventions on learning behaviors and cognitive performance. Additionally, while this study focused on the overall effects of different environmental types, it did not thoroughly examine the specific spatial elements that may influence learning states.

To address these limitations, future research could expand in the following directions: **1)** increasing sample size and diversity to improve population representativeness; **2)** conducting longitudinal studies to evaluate the sustained impact of natural environment exposure on learning efficiency and psychological states over time; and **3)** integrating spatial semantic analysis, individual behavioral trajectory tracking, and multimodal environmental-physiological data to explore precise mechanisms linking specific environmental features with cognitive processes.

In summary, this study introduces a novel perspective through its contextual design and multidimensional measurement framework, systematically elucidating the potential mechanisms by which natural environments support learning efficiency. The findings provide both theoretical and empirical foundations for optimizing the spatial design of educational environments, while laying the groundwork for developing equitable and health-promoting green learning spaces.

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Author's Contribution Xiaocong Li: Methodology, Data curation, Resources, Writing - original draft, Writing - review & editing, Supervision. **Yanling Li**: Conceptualization, Software, Investigation, Writing - original draft, Writing - review & editing, Project administration. Funding acquisition.

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